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Safety Assessment of PyroGreen Waste Disposal Operation in Underground Intermediate Level Radioactive Waste Repository

지하 중준위 처분장에서 **PyroGreen** 폐기물 처분 운영에 대한 안전성 평가

2017 년 2 월

서울대학교 대학원

에너지시스템공학부

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Abstract

Safety Assessment of PyroGreen Waste Disposal Operation in Underground Intermediate Level Radioactive Waste Repository

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This thesis study has been conducted for safety assessment of PyroGreen waste disposal operation in a hypothetical underground intermediate level radioactive waste repository. PyroGreen is an innovative partitioning technology has been developed at Seoul National University based on existing pyrochemical technology being tested at Korea Atomic Energy Research Institute (KAERI), Korea. Improvement of Decontamination Factors (DFs) for producing only Intermediate Level Waste (ILW) to remove long-term uncertainty in safety has been the principal reason for the modification. PyroGreen wastes meet WIPP requirements both on alpha-emitter concentration and heat density of waste packages. Geometry and disposal environment for the hypothetical PyroGreen waste repository are

patterned after data from the Gyeongju underground repository, which is the only radioactive waste repository that can accept ILW to some extent in Korea.

The safety assessment of the radioactive waste repository can be divided into one for the post-closure storage period and the other for the disposal operational period. To date, extensive studies have been made with focus on the former issue including efforts for reducing uncertainty in long-term safety assessment. Because operational phase is under high surveillance and management, the latter issue has not received adequate studies.

Since the truck fire accident and waste drum explosion accident on February 5 and February 14, 2014, respectively, at the US Waste Isolation Pilot Plant (WIPP) the safety during the waste disposal operational period receives increasing scrutiny. Especially in the case of an explosion event, consecutive failure of waste packaging inspection and filter system caused radionuclides release to biosphere. The US Department of Energy (DOE) has identified twelve areas of risk contributors including the failure of characterization program, training and qualifying operators and supervisions through the accident investigation report. Through this accident, it has been found that multiple management system installed to ensure defense-in-depth during operation can be failed. Therefore, it is necessary to analyze whether or not the safety can be assured even if an accident occurs, and the accident scenarios discussed in the existing studies are sufficient.

Accident scenarios analyzed in this thesis have been derived from based on existing operational safety assessment scenarios and actual accidents at existing ILW repositories. Flooding is also included because the disposal structures are assumed to have been located below the sea level. Therefore, the final scenarios selected for this study is as follows; 1) fire, 2) deflagration, 3) drop of a box containing drums, 4) seismic event, 5) flooding, 6) rock drop.

The source term from PyroGreen wastes in each accident scenario is calculated by the five factor formula as follows;

$$Source\ Term[Bq] = MAR[Bq] * DR * ARF * RF * LPF$$

MAR: Material at Risk

DR: Damage Ratio

ARF: Airborne Release Fraction

RF: Respirable Fraction

LPF: Leak Path Factor

Each of five factors is defined as below; [1]

Materials at risk= Amount of radioactive material involved in the event.

Damage ratio= Fraction of material impacted by the accident conditions

Airborne release fraction= Fraction of material that can be suspended in the atmosphere and made available for airborne transport

Respirable fraction= Fraction of airborne radionuclides inhaled into the human respiratory system (commonly assumed to include particles 10 microns aerodynamic equivalent diameter or less).

Leak path factor = Factor of representing the division of plume pathway (1.0 is assumed)

To simulate the release of radionuclides based on the Gaussian plume model the atmospheric dispersion factor is used. Atmospheric dispersion factor is a parameter for quantifying airborne concentration [Bq/m3] to unit release rate

[Bq/s] which is affected by wind speed, atmospheric stability, and distance from accident point. Nuclear Safety and Security Commission Notice No. 2012-19, "Survey on Evaluation Criteria of Meteorological Conditions of Reactor Site", presents a method for evaluating nuclides transport using atmospheric dispersion factor during hypothetical accident based on U.S. NRC Regulatory Guideline 1.145.

Based on the calculated radioactivity source term and atmospheric dispersion factor, the consequence from radionuclides release is calculated by GoldSim® . To validate the performance of model, the model was applied to the Gyeongju near surface disposal facility. The public dose results were compared with the results of the radiation environmental impact assessment [2] and it was confirmed that both results agree well. Fire and explosion scenarios, for single drum damage case, are assessed for both underground and surface facilities. It is clearly shown that the impact is much greater if it occurs at a surface facility closer to workers and public. For all scenarios except for flooding, it is assumed that the filtering function of ventilation systems fails for pessimistic evaluation. In the case of accidents occurring in the underground silo, the all radionuclides pass through upper part of the silo and move to the ground area. In flooding scenario, it is assumed that leaching occurs from the surface of all the drums in silo to all the way into the sink ocean. Therefore inhalation dose from local sediment dust and aerosol in marine water, ingestion dose from fish, crustacean, and seaweed, and external dose is calculated by GoldSim® Radionuclide Transport (RT) module which provides solution for contaminant transport equation.

All results confirm that the calculated doses meet the respective regulatory standards with adequate safety margin. As a result, the safety of PyroGreen waste disposal operation in an intermediate level waste repository has been demonstrated for six types of scenarios; 1) fire, 2) deflagration, 3) drop of a box containing drums, 4) seismic event, 5) flooding, 6) rock drop.

Keywords: Assessment of operational Safety, PyroGreen, Intermediate Level Waste Radioactive Waste Repository, Atmospheric Dispersion

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1. Introduction

Since Fukushima accidents in March 2011, the operation of nuclear power plants in many countries is challenged because of public opposition. A public opinion survey across 24 countries found that 62 percent of the respondents opposed nuclear power, and 26 percent of opponents said they changed their previous views due to the Fukushima accident. [3] The loss of public trust in nuclear power plant safety after Chernobyl and Fukushima accidents is one of the major driving force for expanding the spectrum of accident analysis.

Nuclear waste issues present the other half of radiological safety concern. Radioactive waste disposal require adequate retardation mechanisms for source terms from entering into biosphere through both man-made and natural barrier systems. For Low Level Wastes (LLW), retardation periods of several hundred years can be adequate, For High Level Waste (HLW) the period would be over ten thousands of years. [4] While all safety issues must be identified and controlled by the safety regulation of repository system, the unprecedented long post-closure period may threaten the confidence in safety analysis. For examples of HLW repository, Darcy flow velocity, solubility, distribution coefficient, and canister materials corrosion rate contain significant uncertainties that collectively can undermine the safety margin. [5] Additional uncertainties in unexperienced phenomena and/or mechanisms can be appeared in distant future. Therefore, the disposal of Spent Nuclear Fuel (SNF) and HLW from recycling can be criticized by the public due to long-term uncertainty, especially in areas of high population density.

Based on this consideration, PyroGreen, an innovative partitioning technology has been developed at Seoul National University (SNU) to eliminate the need for a HLW repository. It is based on existing pyrochemical technology being tested at Korea Atomic Energy Research Institute (KAERI), Korea. Improvement of Decontamination Factors (DFs) on long-living radionuclides in SNF and HLW has been the principal goal of PyroGreen process development. The advanced decontamination can eliminate HLW while producing only Intermediate Level Waste (ILW) without long-term uncertainty in safety

Most of PyroGreen processes have been patterned after KAERI's pyrochemical technology as described by KIEP-21 [5]. The major differences between KIEP-21 and PyroGreen are 1) improved Cs/Sr recovery by zone refining 2) indigenous Zr hull electrorefining process for recovering trace fuel materials 3) PyroRedSox for decontamination residual U and TRU elements from the molten salt waste stream at the exit of the final residual actinide removal (RAR) process of KIEP-21. The PyroRedSox is a key element of the PyroGreen process with the minimum DF of 20,000. [5]

PyroGreen can help improve public acceptance by removing long-term uncertainties in safety and by utilizing significant experiences with existing ILW repositories around world. While HLW is produced only from SNF and their recycling processes, ILW is produced in general industrial processes such as medical industry as well as nuclear power industry. Also PyroGreen technology can contribute to increasing public acceptance to the waste disposal approaches especially in countries with high population densities where it can be very difficult to find an adequate site for HLW.

Although ILW repository has less uncertainties associated with long-term phenomena, prudent approaches for safety assessment should be carried out in design and operations. A striking example of provoking public distrust due to hasted operations is Asse mine in Germany. Asse mine operating between 1967 and 1978 that emplaced 125,787 packages of LLW and ILW. Because of the proximity between the past mining chambers and adjoining rocks, the natural movement of the rocks developed clefts through which groundwater made flow paths accompanied with instabilities in mining chambers. [6] The German Federal Radiation Protection Agency ordered the retrieval of the total amount of waste from Asses mine.

To prevent such operational failures and to assure the repository safety, extensive studies have been made at other ILW repositories including WIPP. Usually the safety assessment of the radioactive waste repository can be divided into one for the post-closure storage period and the other for the disposal operational period. To date, extensive studies have been made with focus on the former issue including efforts for reducing uncertainty in long-term safety assessment. Because operational phase is under high surveillance and management, the latter issue has not received adequate studies.

However after the two accidents at WIPP, the interest and need about safety assessment during operation is increasing. First accident is the fire accident on February 5, 2014 caused by oil spill from a salt hauler vehicle that is approximately 29 years old. The hydraulic leakage under a sister vehicle led to opening of air lock doors and the loading of combustible oil into the facilities, as was found through accident investigation process carried out after the accident. Such a mistake can increase the chance and consequence of fire. [7]

The second accident at WIPP is a waste drum explosion on February 14, 2014. In the process of repackaging the waste drum, operator(s) accidentally included wheat-based organic absorbent instead of the inorganic absorbent such as zeolite clay absorbent. The presence of organic materials resulted in an exothermic reaction inside the drum, leading to explosions which damaged the surrounding 17 drums. Although the radiation alarm acted and filter system operated in response to the alarm, Pu239, Pu240, and Pu241 were escaped to affect 150 operation crews due to the initial leakage of the filter system. The combination of failure of waste packaging specification, the lapse of inspection and the delayed response of filter system was a complex sequence of event that was not expected to take place at significant likelihood. Although the estimated dose was not significant, it was alarming that multiple system failures in addition to human errors finally resulted in the radionuclide release accidents.

The US Department of Energy (DOE) mentions twelve areas of contribution causes including failure of characterization program and failure of training and qualifying operators and supervisions through the accident investigation report. [8] Through this accident, it has found that multiple management system installed to ensure safety during operation can be failed. It has also found that an unexpected event, like the deflagration accident can occur by human error.

One of the important parts of radioactive waste disposal study is securing safety and reducing uncertainty to gain public confidence. Although the accident at the ILW repository is expected to have low consequence, holistic safety assessment should be made by a very systemic approach. It is necessary to examine whether the safety can be ensured even if an accident occurs, and whether the accident scenarios from the existing studies are sufficient.

Therefore, this thesis aims at developing a radiological safety assessment model for the evaluating accidents that can occur during the operation phase of an underground ILW repository. By using this model, safety assessment of PyroGreen waste disposal operation in underground ILW repository is conducted.

2. Literature Review

2.1 Past studies of Scenario Development Process

2.1.1 Development Features Events and Processes

The Features Events and Processes (FEPs) is relevant factors affecting disposal facilities performance and safety. By combining each FEP can develop a single scenario. For example, the normal scenario consists of FEPs with a probability of occurrence of 1, selected as the criteria for the evaluation of long-term radiation safety and performance after radioactive waste repository closure. [9] Therefore the key activities in development of safety assessment are the comprehensive identification of FEPs, and the selection of FEPs that should be included in quantitative analyses.

A working group on the identification and selection of scenarios for repository safety assessment was set up by the OECD Nuclear Energy Agency (NEA) Performance Assessment Advisory Group (PAAG) in 1987. In their final report of a scenario development and application, it was suggested that the development of an international database of FEPs which provides an indication of completeness of an assessment. [10] The development of international FEP list based on the experience of each country.

In the early 1980s the IAEA suggested a list, “Suggested checklist of phenomena” potentially relevant to release scenarios for repositories. [11] It become a starting point for scenario development. During the 1980s a variety of methodologies for developing scenario lists have been developed. But all these lists focused on scenario initiating phenomena, or phenomena that would lead to changes in the disposal system or the pathways for radionuclide release and migration. In the late 1980s, however the Swedish Nuclear Fuel and Waste Management Company (SKB) and Nuclear Power Inspectorate (SKI) develop a list focused relevant factors performance including engineered barriers and geosphere for a repository for spent fuel in Swedish bedrock. The developing procedure is as follows. [10]

1) Lists of FEPs were derived by four groups of experts working semi-independently.
2) Efforts were mate to record all potentially relevant FEPs, not just scenario initiating or potentially disruptive phenomena
3) For each FEP a “memo comment” was written which recorded information on the process, its effects, references to the process and whether the FEP could be omitted from quantitative analysis,

This methodology were basis for formula methods of FEP analysis. These days complex and massive FEPs are communicated through computer database.

2.1.2 Scenarios for Operation Phase

Basically, the development of scenarios is based on the FEPs. These FEPs can changes affected by disposal environment, engineered system, and disposal concepts. In ROK, FEPs was developed for post-closure period by KAERI in 2012. [9] However, FEPs for operational phase have not been developed yet. The international FEP list also has the limits for discussion and analysis within post-closure safety assessments. In Finland, the analysis using FEPs has been carried out. [12] But it is difficult to consider it as an operational accident scenario analysis because it focuses on analyzing the impact of excavation and operational in the thermal, mechanical, hydrological and chemical conditions on future repository performance. Accidents occurring during operation are often caused by unexpected human acts, and it is difficult to express these human behaviors as a relevant factor like FEP.

Therefore the hazard analysis method developed DOE for WIPP is the suitable method at present. Hazard analysis consider the complete spectrum of events that may occur caused by facility operations, natural disasters, and man-made external events. The description of overall process employed in this thesis is as follows. [13]

1) Information gathering process: Hazards were primarily identified through the development of lists of known hazardous energy and material sources and identifying hazardous locations. Information for identifying hazards and determining their applicability to the facility was obtained, as applicable, from the following sources:

   Existing project, safety, and environmental documents
   Design drawing and reviews
   Test plans and studies
   Process and equipment data
   Consultations with facility, system, and process experts

2) Screening process: Derive the risk level based on the frequency and consequence levels for each event and exclude low risk level events. Table

2.1 shows frequency levels, Table 2.2 shows consequence levels and Table 2.3 shows risk levels.

3) Considering preventive and mitigative features: Identifies and assesses associated preventive and mitigative controls within the facility that form the basis for defense-in-depth against adverse consequences to the workers, public, and environmental from hazardous events. Even scenarios with high risk levels are excluded if these actions are expected to lower the frequency or consequence of the events.

4) Quantitative Analysis: Conduct quantitative analysis to selected scenarios.

Table 2.1 Frequency levels [13]

Frequency Level	**Frequency**	**Qualitative Description**
Anticipated (A)	$f > 10^{-2}/yr$	Events that might occur several times during the lifetime of the facility
Unlikely (U)	$10^{-4}/yr < f < 10^{-2}/yr$	Events not anticipated to occur during the lifetime of the facility
Extremely Unlikely (EU)	$10^{-6}/yr < f < 10^{-4}/yr$	Events that will probably not occur during the lifetime of the facility
Beyond Extremely Unlikely (BEU)	$f < 10^{-6}/yr$	All other events

Table 2.2 Consequence levels [13]

Consequence Level	**MOI***	**Collocated Worker**	**Facility Worker**
High	$\geq 25\ rem\ TED**$	$\geq 100\ rem\ TED$	Prompt death, serious injury
Moderate	$\geq 5\ rem\ TED$	$\geq 25\ rem\ TED$	No distinguishable threshold
Low	$< 5\ rem\ TED$	$\geq 25\ rem\ TED$	No distinguishable threshold

*MOI: Maximally Exposed Offsite Individual
**TED: Total Effective Dose

Table 2.3 Risk levels derived by frequency and consequence [13]

Consequence Level	Frequency Level			
	BEU	EU	U	A
High	Ⅲ	Ⅱ	Ⅰ	Ⅰ
Moderate	Ⅳ	Ⅲ	Ⅱ	Ⅱ
Low	Ⅳ	Ⅳ	Ⅲ	Ⅲ

Ⅰ: Combination of conclusions from risk analysis that identify situations of major concerns
Ⅱ: Combinations of conclusions from risk analysis that identify situations of concern
Ⅲ: Combinations of conclusions from risk analysis that identify situations of minor concern
Ⅳ: Combinations of conclusions from risk analysis that identify situations of minimal concern

BEU: Beyond Extremely Unlikely
EU: Extremely Unlikely
U: Unlikely
A: Anticipated

2.2 PyroGreen Process

This thesis is conducted for safety assessment of PyroGreen waste disposal operation in underground intermediate level radioactive waste repository. Seoul National University has been develop the innovative partitioning technology, designated as PyroGreen. It is based on existing pyrochemical technology being tested at Korea Atomic Energy Research Institute (KAERI), Korea. Figure 2.1 describes the similarity and differences between above two processes. [5]

The basic process framework based on pyro-based technology such as voloxidation, electrolytic reduction, electrorefining and electrowinning is same. However, the PyroGreen process performs Cs and Sr recovery, Zr hull electrorefining and selective oxidation of rare earth elements to increase DFs. [5]

1) Cs/Sr recovery by zone refining: Because the Cs and Sr are major heat sources, it is necessary to recover from molten salts during the PyroGreen process. Zone refining process can achieve DF of 300 based on experimental results and three dimensional modeling.
2) Zr hull electrorefining process for recovering Zr: Spent nuclear fuel Zr hulls were irradiated during the nuclear power plant operation. There would be various radioisotopes classified as activation products, fission products and actinides elements. [14] Because of the penetration depths, volumetric decontamination process is needed. Zr is recovered by electrochemical reactions in LiCl-KCl molten salts.
3) Selective oxidation process designated PyroRedSox: During the final residual actinide removal, RAR process, developed by KAERI it was

reported that DF of 1,000 for actinides can be achieved. [15] To meet the PyroGreen goal DF or 20,000 is required. [16] Therefore, SNU developed the PyroRedSox process, separating the U and TRU elements from the molten salt consumed during the final residual actinide removal (RAR) process.

The reason for raising the DF is to avoid many uncertainties due to HLW disposal and to improve the public acceptance. Through these processes, the PyroGreen goal is to satisfy the WIPP waste acceptance criteria. The WIPP tested both normal and breakout scenarios such as human intrusion and satisfied of all with high margins. The waste acceptance criteria for WIPP is as follows. [17]

1. Alpha-emitting nuclide concentration,

A. 18.4 Ci/m3 for contact-handled waste

B. 2.58 Ci/m3 for remote-handled waste

2. Heat density of waste package,

A. 0.5 Watt/m3 for contact-handled waste

B. 0.4 Watt/m3 for remote-handled waste

The goals on DFs to meet these criteria and the achievable DF from PyroGreen are summarized in Table 2.4

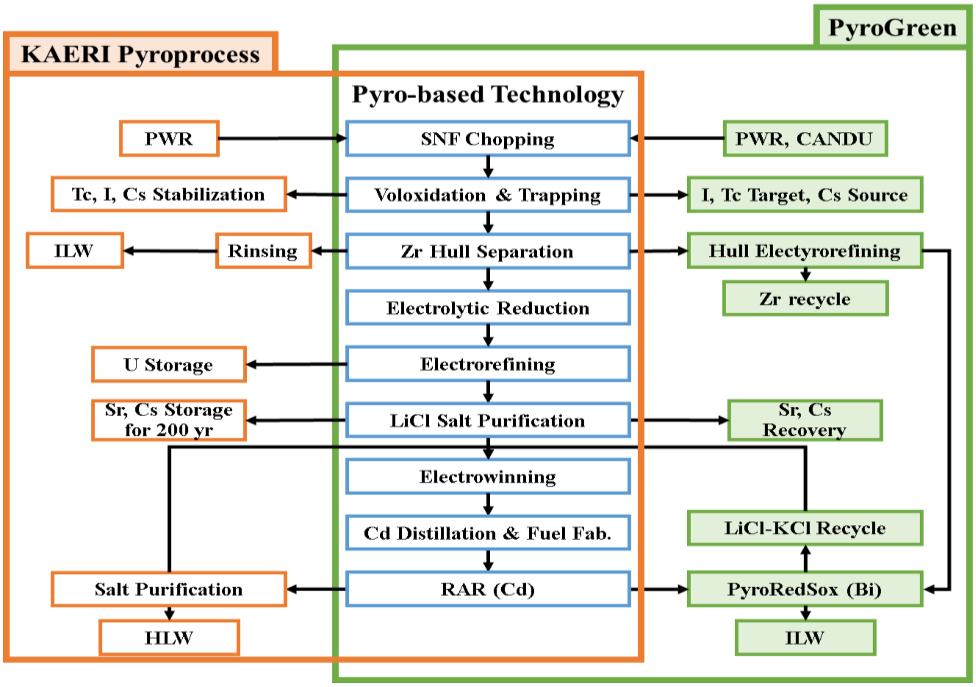

Figure 2.1 Similarities and differences of KIEP-21 and PyroGreen [5]

Table 2.4 Goal and achievement of decontamination factors for PyroGreen [5]

Elements		DF-Goal	PyroGreen process	Demonstration of feasibility (Separation rate)		Achieved DF	
				Experimental data	**Numerical Model**	**Experiment**	**Model**
Tc		50	Voloxidation	99%[c]	N.A.	100	N.A.
I		50	Voloxidation	99%[d]	N.A.	100	N.A.
Cs		300	Voloxidation	98% (Voloxidation)[e]	N.A.	50	N.A.
			Zone refining	90% (Zone Refining)[f]	90% [ref]	10	10
Sr		300	Carbonization	99.6%(Carbonization)[g]	N.A.	250	N.A.
			Zone refining	90%(Zone Refining)[f]	90% [ref]	10	10
Zr. Hull	TRU	67[h]	Hull electrorefining	In progress	100%[ref]	N.A.	Over 1,000
	Cs	7[i]		In progress	100%[ref]	N.A.	Over 1,000
U		20,000	RAR	99.9% [a]	99.9%[ref]	1,000	N.A.
			PyroRedSox	99% [b]	N.A.	100	N.A.
TRU		20,000	RAR	99% (RAR)[a]	98.5%	100	60
			PyroRedSox	99% (PyroRedSox)[b]	N.A.	100	N.A.

[a] [14]
[b] [17]
[c] [18]
[d] [19]
[e] [20]
[f] [21]
[g] [22]
[h] Decontamination factor to meet LLW criteria of ROK
[i] Decontamination factor to meet LLW criteria of ROK
N.A. Not Available

3. Rationale and Approach

3.1 Problem Definition

Although accidents during operation are often caused by unexpected human acts, it is difficult to develop relevant factors that deal with all these behaviors. Therefore, the multiple management system and surveillance system is built to prevent these accidents and mitigate the consequence of accidents. It is anticipated that this system will be able to prevent the release of radionuclide sufficiently if accidents occur.

However, through the accident in February, 2014 at WIPP it was confirmed that these systems can be failed. Also protection program and protective actions are pointed out less than adequate such as opening air lock doors and loading combustible materials. [7] So far, mitigative and preventive measures have been considered in the scenario development. But accident evaluations except these measures should be considered. Therefore, it is necessary to analyze whether the safety can be ensured even if an accident occurs, and whether the accident scenarios discussed in the existing studies are sufficient.

The goal of this thesis is to develop of operational accident evaluating model for underground Intermediate Level Waste (ILW) repository. Based on this model, the safety assessment for disposal PyroGreen waste is carried out for total of eight scenarios

3.2 Rationale

The overall approach of this research is shown in Figure 3.1. It consists of the following steps; model development, model benchmark and data scenario construction, scenario model data base, model application. For the defined thesis problem, results of the thesis are expected to possess;

Practicality: Scenarios which have not been evaluated previously have been proposed. It is possible to see the changing results by weather conditions such as wind speed or atmospheric stability class. The amount of breathable nuclides emitted during accidents is determined using DOE experimental data. [13] The movement of these radionuclides except from the flooding scenario is assessed on the basis of atmospheric dispersion factors, which can be derived from the Gaussian plume model. As an appropriate assessment tool for model involving radionuclides, the GoldSim® Radionuclide Transport (RT) module which is developed to support the Yucca Mountain Project is applied. Through the results of this thesis, it can be confirmed that PyroGreen waste can be secured during operation phase disposing it underground intermediate level waste repository.

Integrity: Benchmarking is performed on seismic event and fire scenarios through application to Gyeongju near surface disposal facility, to ensure the reliability of the model. The reference used for benchmarking is the second stage disposal facility environmental impact assessment conducted by the Korea radioactive waste agency [2]. The evaluation method is ensured by according to the study of the Nuclear Industry Radioactive Waste Executive (NIREX) from a conservative point of view. [24]

Originality: List of scenarios is created based on previously developed scenarios and actual accident cases. Fail of the mitigative and preventive measures have been considered in the scenario development process. Because of the hypothetical repository is located below the sea level, flooding scenarios is added and nuclides transport to the far ocean is evaluated.

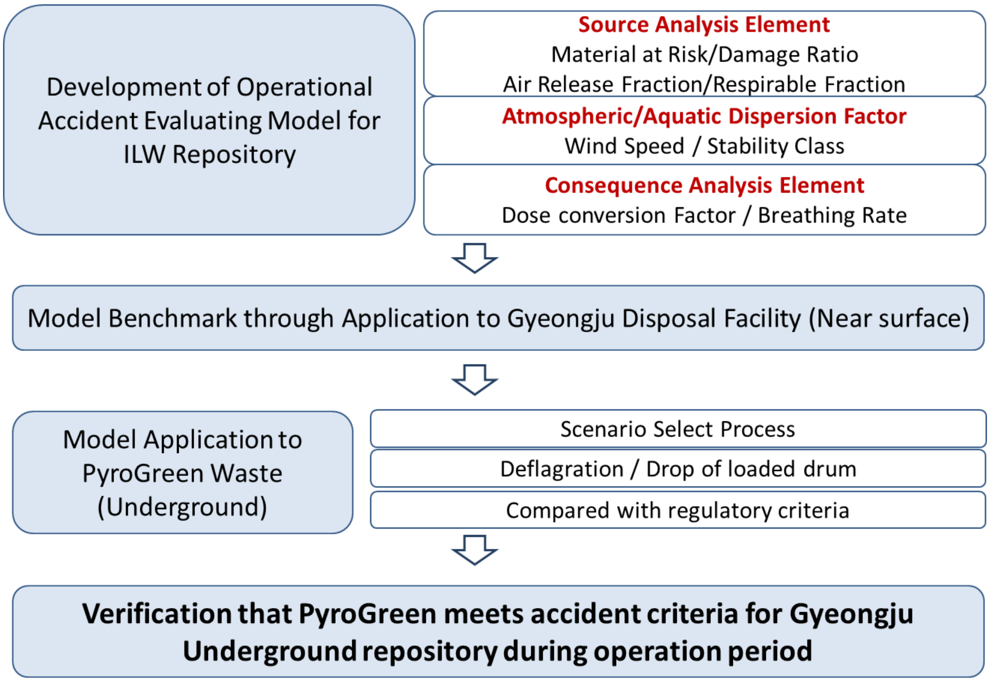

Figure 3.1 Overall approach of research

4. Model Development for Operational Accidents at ILW Repository

In this chapter, the basic concepts of the model and the elements will be explained. This model assumes the situation of disposal at a hypothetical intermediate underground repository.

4.1 GoldSim® Code for Environmental Impact Assessment

The GoldSim® is software based on Monte Carlo simulation which supports decision and risk analysis by simulating future performance while quantitatively representing the uncertainty and risks inherent in all complex systems. GoldSim® provides sub-modules including contaminant transport module and radionuclide transport module specific to each field.

GoldSim® Radionuclide Transport (RT) module which provides solution for contaminant transport equation is specialized for simulating the movement of nuclides through repository engineered system and host rock. This module developed to assist the United States Department of Energy in the evaluation of radioactive waste management alternatives. Also it is currently being used by regulatory and research institutes worldwide including Republic of Korea.

The RT module allows decay chains to be simulated and provides an option to utilize a large built-in database of radionuclide decay data including species, decay rates and daughter products from International Commission for Radiation

Protection (ICRP)'s Publication No.107. Also it can link to an extensive database of radionuclides.

The RT module provides a special element called a Source and Network Pathway. The Source element can be used to simulate the complex release mechanisms of contaminants from engineered systems. Network pathways provide a computationally efficient way to simulate large, complex networks of one-dimensional conduits in order the describe contaminant transport through fractured rock systems. [25]

To validate the GoldSim® calculation ability of nuclide migration, benchmarking for compared nuclide release rate is conducted. The reference case is H12 report supporting safety assessment of the geological disposal system in Japan. [26] The fundamental model design is based on established GoldSim®, the components and geometry data, inventory and flow-related transport properties are quoted in reference case. The nuclides transport model compartments as shown in Figure 4.1.

Figure 4.2 shows the comparison of nuclides release rate from engineered barrier system (EBS). The results of GoldSim® model and reference case are matched well.

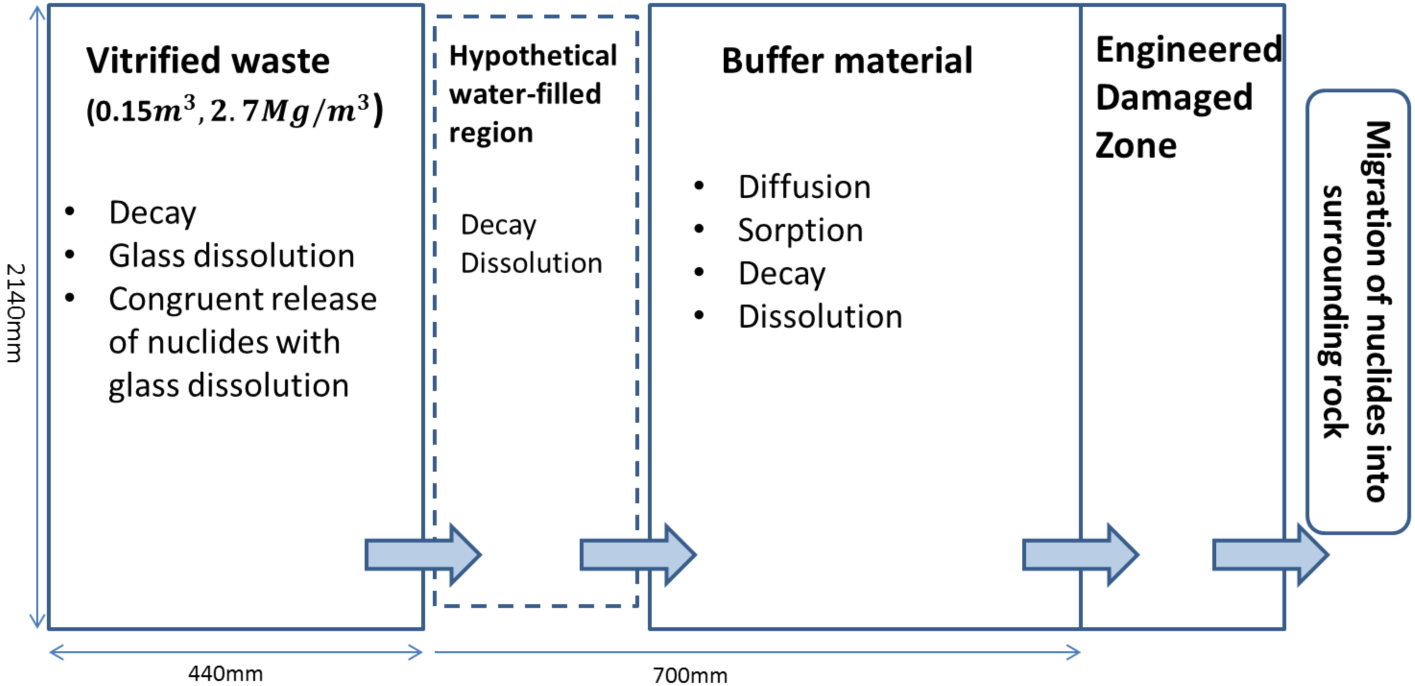

Figure 4.1 Nuclide migration process in the EBS

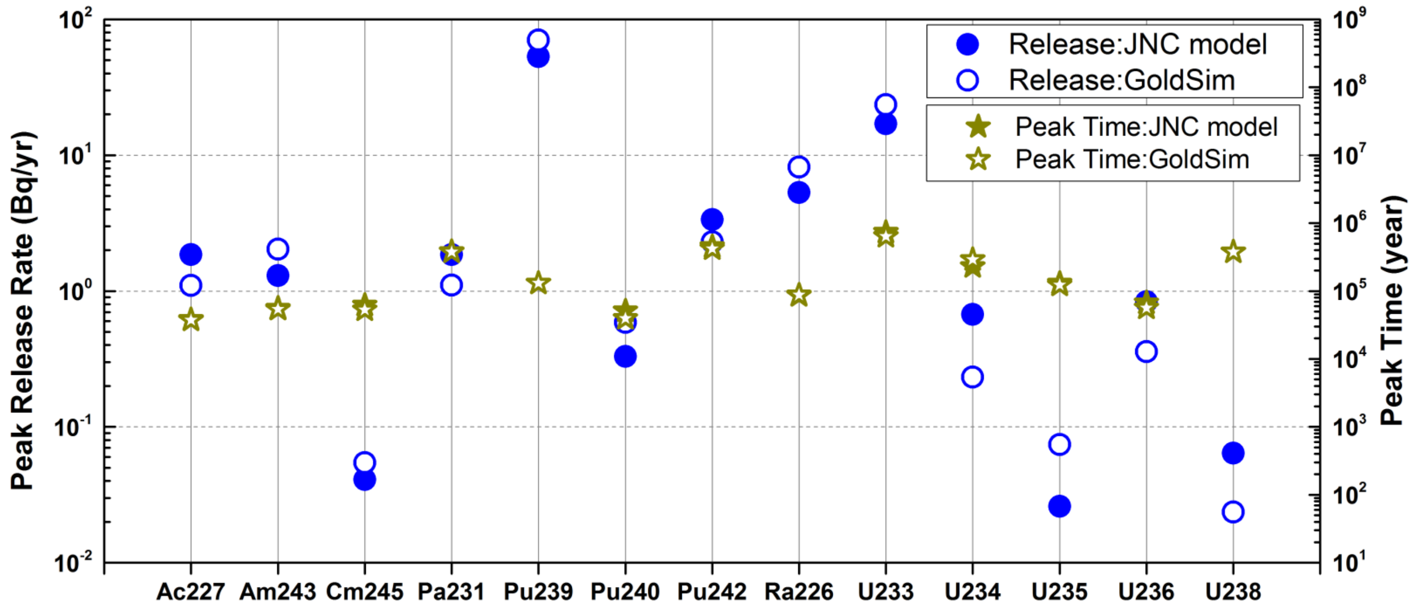

Figure 4.2 Release rate and peak time comparison

4.2 Source Term Analysis

The method of calculating the effect of nuclide release from operation accident can be divided into two steps. The first step is to derive the amount of airborne respirable radioactive material released to the environment which is called source term. The source term is calculated using the five-factor formula, following equation. [13]

$$Source\ Term = MAR * DR * ARF * RF * LPF$$

MAR: Material at Risk

DR: Damage Ratio

ARF: Airborne Release Fraction

RF: Respirable Fraction

LPF: Leak Path Factor

Complex postulated accident scenarios may employ multiple calculations that are added together to get the source term for the event. More specifically, the Waste Isolation Pilot Plant Documented Safety Analysis defined each element as follows. [13]

MAR is expressed as a product of the number of waste containers or waste containers assemblies involved in the postulated event. DR is fraction of material actually impacted by the accident conditions.

*ARF*RF is estimating the amount of airborne materials generated from accidents involving solids, liquids, gases or surface contamination. An LPF of 1 was conservatively assumed.*

4.3 Consequence Analysis

4.3.1 Atmospheric Dispersion Factor

Atmospheric dispersion factor(x/Q) is a factor for quantifying airborne concentration (Bq/m3) to unit release rate (Bq/s). Nuclear Safety and Security Commission Notice No. 2012-19, “Survey on Evaluation Criteria of Meteorological Conditions of Reactor Site”, presents a method for evaluating nuclides transport using atmospheric dispersion factor during hypothetical accident based on U.S. NRC regulatory guideline 1.145. The type of release to the environment through the ventilation system and leakage of the reactor building is called surface release. In this case, Gaussian plume model is used the derivation of the atmospheric diffusion factor for the center line of the plume. The formula is as follows. [27]

$$\frac{x}{Q} = \frac{1}{U_{10}\left(\pi\sigma_y\sigma_z+\frac{A}{2}\right)} \tag{1}$$

$$\frac{x}{Q} = \frac{1}{U_{10}\left(3\pi\sigma_y\sigma_z\right)} \tag{2}$$

$$\frac{x}{Q} = \frac{1}{U_{10}\pi\sum_y\sigma_z} \tag{3}$$

x/Q= Atmospheric Dispersion Factor(s/m3)
U= Wind speed at 10m elevation from ground (m/s)
A= Area (m^2)

∑y=Horizontal Diffusion Coefficient reflecting the meandering effect(m)

σy= Horizontal Diffusion Coefficient(m)

σz= Vertical Diffusion Coefficient(m)

When the wind speed is lower than 6m/s and the atmospheric stability is neutral (Stability class D) or stable (Stability class E, F, G), additional diffusion due to meandering of the plume in the horizontal direction is considered. In these meteorological conditions, a higher value is selected among the atmospheric diffusion factors evaluated by equation (1) and equation (2), and a larger value is selected by comparing this value with the atmospheric diffusion factor estimated by equation (3)

In general, the diffusion coefficient in the Gaussian plume model is estimated as a function of distance to atmospheric stability. Atmospheric stability is estimated from the temperature difference along the height. Table 4.1 shows classification of stability class. [28] Because of the variety of environmental and weather conditions the diffusion coefficient implies a log of uncertainty. The estimation diffusion coefficient is basically obtained from the Pasquill-Gifford curve obtained from the experimental data obtained by discharging the tracker for a short period of time over a flat terrain. [29] The US NRC recommends applying Eimutis-Konic derived equations when deriving the diffusion coefficient as follows.

$$\sigma_y = a\left(\frac{x}{1000}\right)^{0.894}$$

$$\sigma_z = c\left(\frac{x}{1000}\right)^{d} + f$$

The constants determined according to the atmospheric stability are shown in Table 4.2. If the atmosphere is stable (Class E, F, G) and the wind speed is lower than 6m/s, correct the horizontal diffusion coefficient using the meandering effect correction factor obtained from the experiment. Experimental results show that the meandering effect of plume increases the diffusion of nuclides 1.5 to 2.5 times. [30] Figure 4.3 shows the atmospheric diffusion factor calculated as above assuming a wind velocity of 1 m/s.

Table 4.1 Classification of stability class [28]

Stability	Class	Temperature reduction rate ($\Delta T/\Delta z$, ℃/100m)	$\sigma\theta$* (deg)	R_b**
Very unstable	A	$(\Delta T/\Delta z) \leq -1.9$	$22.5 < \sigma\theta$	$Rb \leq -0.35$
Unstable	B	$-1.9 < (\Delta T/\Delta z) \leq -1.7$	$17.5 < \sigma\theta < 22.5$	$-0.35 < Rb \leq -0.18$
Weak unstable	C	$-1.7 < (\Delta T/\Delta z) \leq -1.5$	$12.5 < \sigma\theta < 17.5$	$-0.18 < Rb \leq -0.04$
Neutral	D	$-1.5 < (\Delta T/\Delta z) \leq -0.5$	$7.5 < \sigma\theta < 12.5$	$-0.04 < Rb \leq -0.01$
Weak stable	E	$-0.5 < (\Delta T/\Delta z) \leq 1.5$	$3.8 < \sigma\theta < 7.5$	$-0.01 < Rb \leq 0.07$
Stable	F	$1.5 < (\Delta T/\Delta z) \leq 4.0$	$2.1 < \sigma\theta < 3.8$	$0.07 < Rb \leq 0.13$
Very stable	G	$4.0 < (\Delta T/\Delta z)$	$\sigma\theta < 2.1$	$0.13 < Rb$

*Wind direction standard deviation

**Bulk Richardson Number

Table 4.2 Constants of diffusion coefficients recommended by U.S. NRC [27]

Stability class	A	x≤1km			x>1km		
		C	d	f	c	d	F
A	213	440.8	1.942	9.27	459.7	2.094	-9.6
B	156	106.6	1.149	3.3	108.2	1.098	2
C	104	61	0.911	0	61	0.911	0
D	68	33.2	0.725	-1.7	44.5	0.516	-13
E	50.5	22.8	0.678	-1.3	55.4	0.305	-34
F	34	14.35	0.74	-0.35	62.6	0.18	-48.6

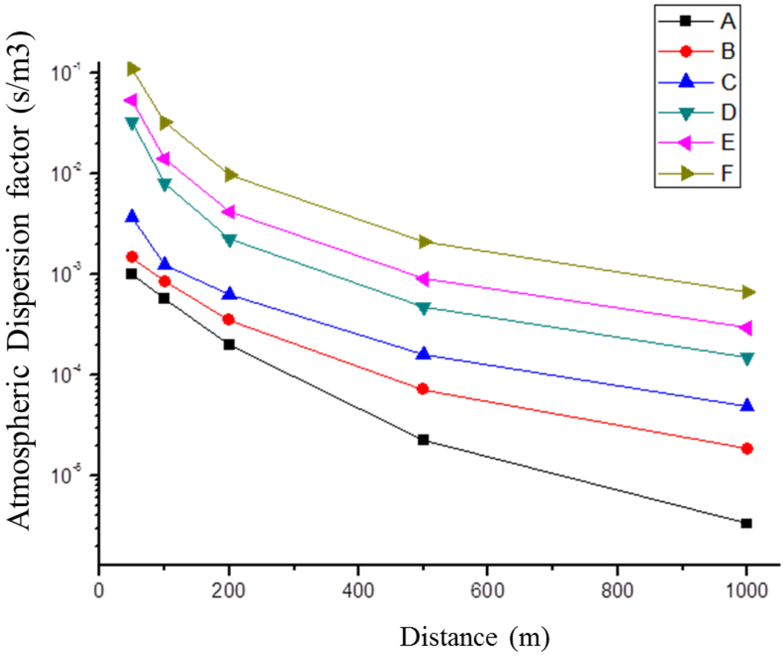

Figure 4.3 Atmospheric dispersion factor at wind speed 1m/s

4.3.2 Consequence

Because the operation phase of repository is dry condition, atmospheric transport is the only significant release pathway during normal operations and accident conditions. The nuclides moved through the atmosphere affect the public, which is assumed to be at the site boundary, and the worker located at a close distance from accident point.

The main exposure pathway of nuclear species from accidents is inhalation and external exposure. However, since the effect of external exposure is very small, about 1/1000 of the effect of inhalation, focus on the inhalation. The breathing rate is 3.3E-4m^3/s from International Commission on Radiological Protection (ICRP) publication. [13] The schematic for basic concept of consequence analysis is shown in Figure 4.4.

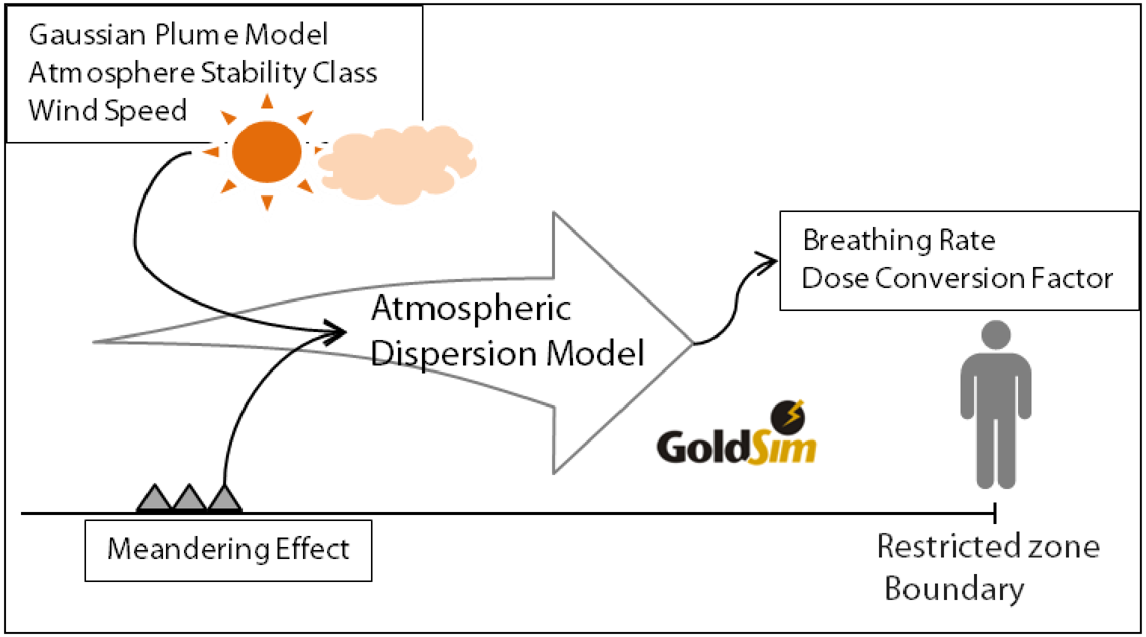

Figure 4.4 Basic concept of consequence analysis

5. Model Benchmark through Application to Gyeongju Disposal Facility

5.1 Reference Case

To verify the performance of model, the model was applied to the Gyeongju near surface disposal facility. The public dose results were compared with the results of the radiation environmental impact assessment. According to the study of the Nuclear Industry Radioactive Waste Executive (NIREX), the model was assumed that all the gas in the underground passes through the upper part of the silo and moves to the upper ground area of the silo and emerges into the ecosystem from a conservative point of view. [24] So it can also applicable to near surface facility.

Gyeongju environmental impact assessments were made for 4 types of accident using DFINT, DFEXT and MicroShield Code. Table 5.1 shows a description of each type of accident. Seismic accident was selected because it was expected to have the largest impact among events caused by natural disasters.

Among these events a scenario of single container damage type and a scenario of total container damage type were selected for benchmarking.

1) Drop of drum during loading process

2) Seismic event that results in a building collapse.

Table 5.1Description of accident type [2]

Accident Type	Description
1.0	Drop
1.1	Drop while transporting by truck
1.2	Drop during loading process
1.3	Drop of loaded drum in the near surface repository
2.0	Fire
2.1	Fire during transport
2.2	Fire inside near surface repository
3.0	Off site
3.1	Plane crash
3.2	Seismic Event
4.0	Criticality
4.1	Criticality accident during normal operation
4.2	Criticality accident caused by operation accident

5.2 Model Application

The current status of the near surface disposal facility structures under consideration is shown in Figure 5.1. For the 200L container standard, grouting for injecting the filling material into cracks is 10cm for the prevention of leaks and safety. In this case, there are 710 drums on one floor and 6390 drums can be stacked per disposal facility. [31]

There are four types of wastes to be disposed at the near surface disposal facility; spent resin, waste concentrate, spent filter, dry active waste. The radioactive waste inventory data used in the evaluation model are shown in Table 5.2. Damage ratio, air release fraction and respirable fraction used in the model are shown in Table 5.3 Damage ratio was derived from the experimental data on the 200L drum. [13] Air release fraction and respirable fraction data was derived from DOE Handbook 3010-94. [32] Inhalation dose coefficients are shown in Table 5.4

Figure 5.2 shows the comparison result of public dose between GoldSim® model and reference case. The results agree well with each other.

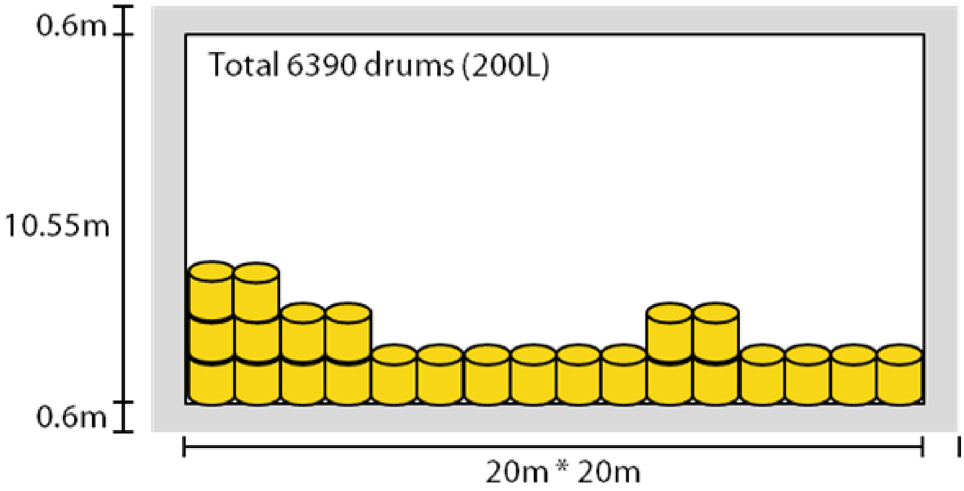

Figure 5.1 Near surface disposal facility concept [31]

Table 5.2 Inventories for benchmarking case

Nuclide	Radioactivity(Bq)
H-3	2.19E+10
C-14	2.07E+09
Fe-55	3.88E+11
Co-58	5.16E+09
Co-60	3.33E+10
Ni-59	4.21E+08
Ni-63	1.44E+10
Sr-90	2.52E+08
Nb-94	9.75E+05
Tc-99	1.93E+08
I-129	8.06E+04
Cs-137	2.45E+09
Ce-144	6.29E+06
Total Alpha	4.67E+11

Table 5.3 Damage ratio, air release fraction and respirable fraction for benchmark case

	Drum Drop	Seismic Event	Reference
Number of Drum	1	6390	
Damage Ratio	1	0.1	DOE-STD-5506-2007, Preparation of safety basis documents for transuranic waste facilities Table 4.4.4-1. Container drop and impact damage ratios Table 4.4.5-1 Damage ratios for containers impacted by seismic debris
Airborne Release Fraction*Respirable Fraction	2.0E-3	1.0E-4	DOE Handbook 3010-94, Airborne release fractions/rates and respirable fractions for nonreactor nuclear facilities

Table 5.4 Inhalation dose coefficients [33]

Nuclide	Sv/Bq
H-3	4.1E-11
C-14	5.8E-10
Fe-55	7.7E-10
Co-58	1.5E-09
Co-60	2.90E-08
Ni-59	1.30E-10
Ni-63	4.40E-10
Sr-90	2.80E-08
Nb-94	1.70E-09
Tc-99	6.40E-10
I-129	1.10E-07
Cs-137	1.38E-08
Ce-144	3.40E-08
Total Alpha	5.7E-7

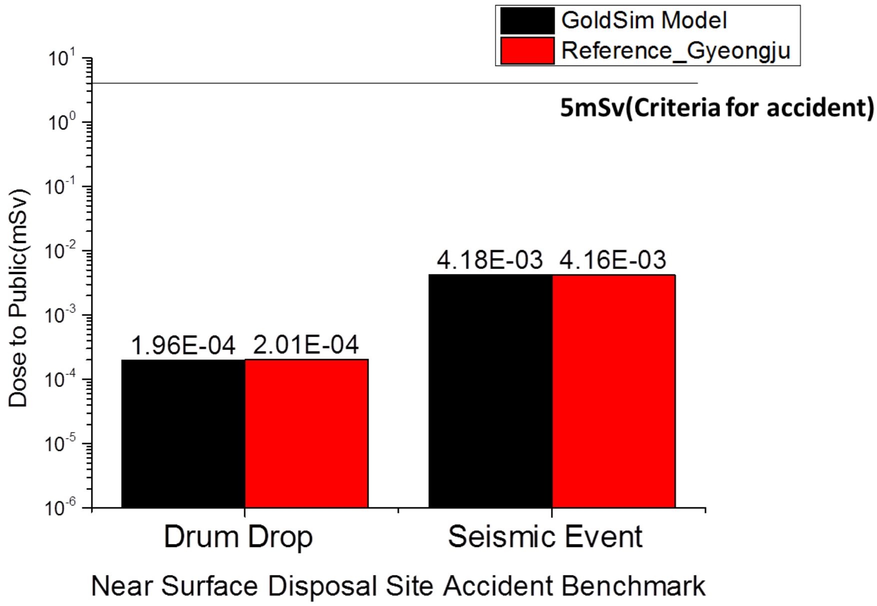

Figure 5.2 Comparison of the results between GoldSim® model and reference case

6. Assessment of Intermediate Level Waste Repository

6.1 Scenario Development

As mentioned in Chapter 2, the process of developing scenarios consists of four steps; 1) information gathering process 2) screening process 3) considering preventive and mitigative features 4) quantitative analysis. These procedures have been used in many countries, including the United States, the United Kingdom and Sweden. In the US, seven hazard categories were derived from the first stage, expert consultation; direct exposure, criticality, external hazards, deflagration, natural phenomena hazard, fire and loss of confinement. External hazards are threats from external factors such as airplane collisions. Among these, the direct exposure, criticality and external hazards which are estimated to have low risk levels were screened out. Deflagration and natural phenomena hazard were also excluded, taking preventive and mitigative measures into account in the next step. For example, the mitigative engineered features of the deflagration scenario mentioned in the DOE are as follows. [1]

To further ensure compliance with the WIPP WAC, TRU waste containers are visually inspected for signs of "suspect" containers and handled in accordance with specific actions to ensure protection of workers. This control ensures that if WIPP suspects a container of not complying with the WIPP WAC or if WIPP is informed by a waste generator that a container does not comply or is suspected of being *noncompliant, then further handling of that container will be performed in accordance with an acceptable response plan. This response plan will contain provisions to protect the worker from hazards associated with storage and/or movement of the suspect container*

Through this process fire and loss of confinement hazard categories were finally selected. However, considering the drum explosion accident in February 2014 and the collapse of the ceiling accident in October 2016, additional scenarios need to be evaluated. Also flooding of the underground disposal structures during operation need to be evaluated, since Korean disposal structures are located 80 meters below sea level.

Therefore, the final scenarios selected for this study is as follows; fire, deflagration, drop of a box containing drums, seismic event, flooding, rock drop. fire and explosion scenarios, which are single drum damage scenarios, are assessed for both underground and surface facilities, as they are expected to be the most dangerous to occur in pre-acquisition storage facilities on the surface. These scenarios are summarized in Figure 6.1

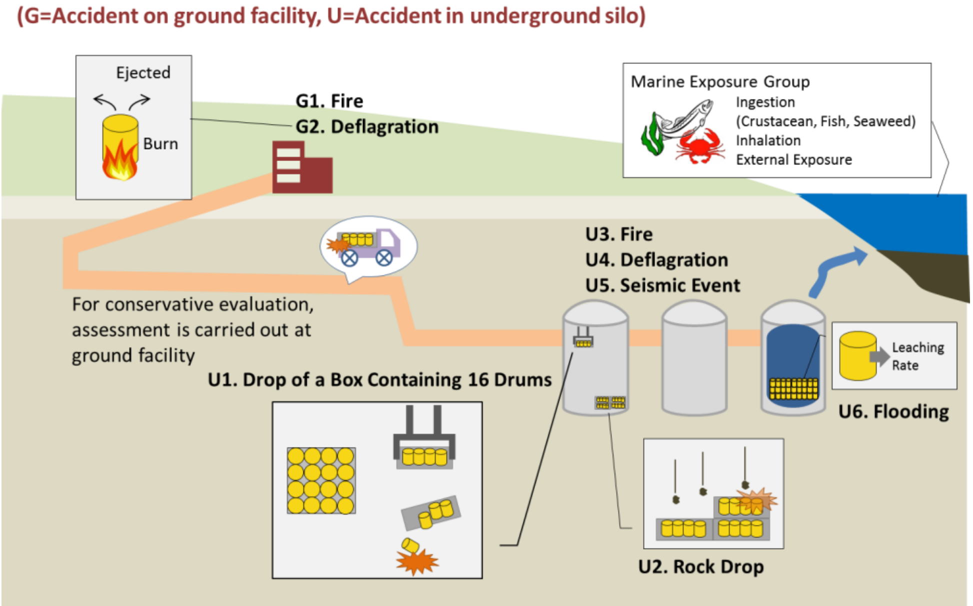

Figure 6.1 Scenarios derived for evaluation

6.2 Accident Modeling and Input Data

The damage ratio, airborne release fraction, and respirable fraction used in each scenario and references to the above data are summarized in Table 6.1. Damage ratios are experimental data from preparation of safety basis documents for transuranic waste facilities. [13] Airborne release fractions and respirable fractions are quoted DOE handbook 3010-94. [32] All data were used for vitrified wastes, because the rare earth wastes produced in the PyroRedSox process of the PyroGreen, are designed to be vitrified by the optimum glass, called as PG14. For all scenarios, it is assumed that the ventilation system fails.

6.2.1 Drop Scenario

The causes and progress of drop scenario is shown in Figure 6.2. On the top of the underground silo, there is a gripper which is a device for moving the box containing up to 16 drums. In the placement process, malfunction of gripper and mistake of workers can lead the drop of box. For conservative evaluation, it is assumed that the dropped drums are 100% damaged and the inner nuclides are released.

6.2.2 Deflagration Scenario

The causes and progress of deflagration scenario is shown in Figure 6.3. The impact is greater if it occurs at a surface facility closer to workers and the public. Therefore, it is evaluated including both the occurrence in the surface facility and the occurrence in the underground silo. In the case of accidents occurring in the underground silo, the all radionuclides pass through upper part of the silo and move to the ground area. During the loading process or loading, failure of proper packaging, exothermic reaction and strong impact can lead the deflagration event. The technical bases for conservative estimation of data establishes experiments and review of the literature. During the deflagration event, the radioactive material is released to the environment from three accident stresses; 1) during the flexing in air, 2) unconfined burning of a fraction of the material ejected 3) burning of the remaining materials inside the drum. [13]

6.2.3 Fire Scenario

The causes and progress of fire scenario is shown in Figure 6.4. During the operation, equipment aging and oil spillage may cause the fire. It can be caused by a variety of causes, and occur as a result of other scenarios. In February 2014 fire events in WIPP, oil from a salt hauler vehicle caused the fire. [7] The fire scenario was also evaluated for its occurrence in the surface facility as well as in the underground silo. In the case of fire occurring in the underground silo, the all radionuclides pass through upper part of the silo and move to the ground area.

6.2.4 Rock Drop Scenario

The collapse of the ceiling, drop of rocks from the seismic events can cause impacts on the waste container. The damage ratio due to the impact on the drum is suggested on WIPP Documented Safety Analysis. The impact of falling objects is most significant when they hit first, and the impact of subsequent collisions is expected to be very small. Because few drums are expected to be affected by this collision, 10 drums were selected for conservative evaluation.

6.2.5 Seismic Event Scenario

The causes and progress of fire scenario is shown in Figure 6.5. The seismic events are expected to have greatest impact on underground silo among natural disasters. It is assumed that seismic events affect all 16,700 drums in the silo. The design standard of domestic underground disposal site is 6.5 of Richter scale. However, it is found that at 100m underground acceleration decreased by more than 30% in the same seismic events through previous studies [34] Also, as shown in Figure 6.7, the compressive strength of the PG14 shall be higher than 115MPa when tested in accordance with ASTM 2010 from US NRC's technical position on waste form. Therefore, the consequence of seismic event is very weak.

6.2.6 Flooding Scenario

It is assumed that leaching occurs from the surface of all 16,700 drums due to flooding. The leaching rates were obtained from PCT experimental data. According to the results of performing 7-day PCT [35] in 40℃ DI water environment with air flow being cut off by conservatively considering underground water temperature of the intermediate-level repository and heat generation of the glass solidified body itself, leaching rates for Si, B, Na, and Li were evaluated to be at a low level below 17.5% of the standard value (2g/m2) and all rare earth elements including Al were not leached out. [5] Inhalation dose from local sediment dust and aerosol in marine water, ingestion dose from fish, crustacean, and seaweed, and external dose were considered as shown in figure 6.6

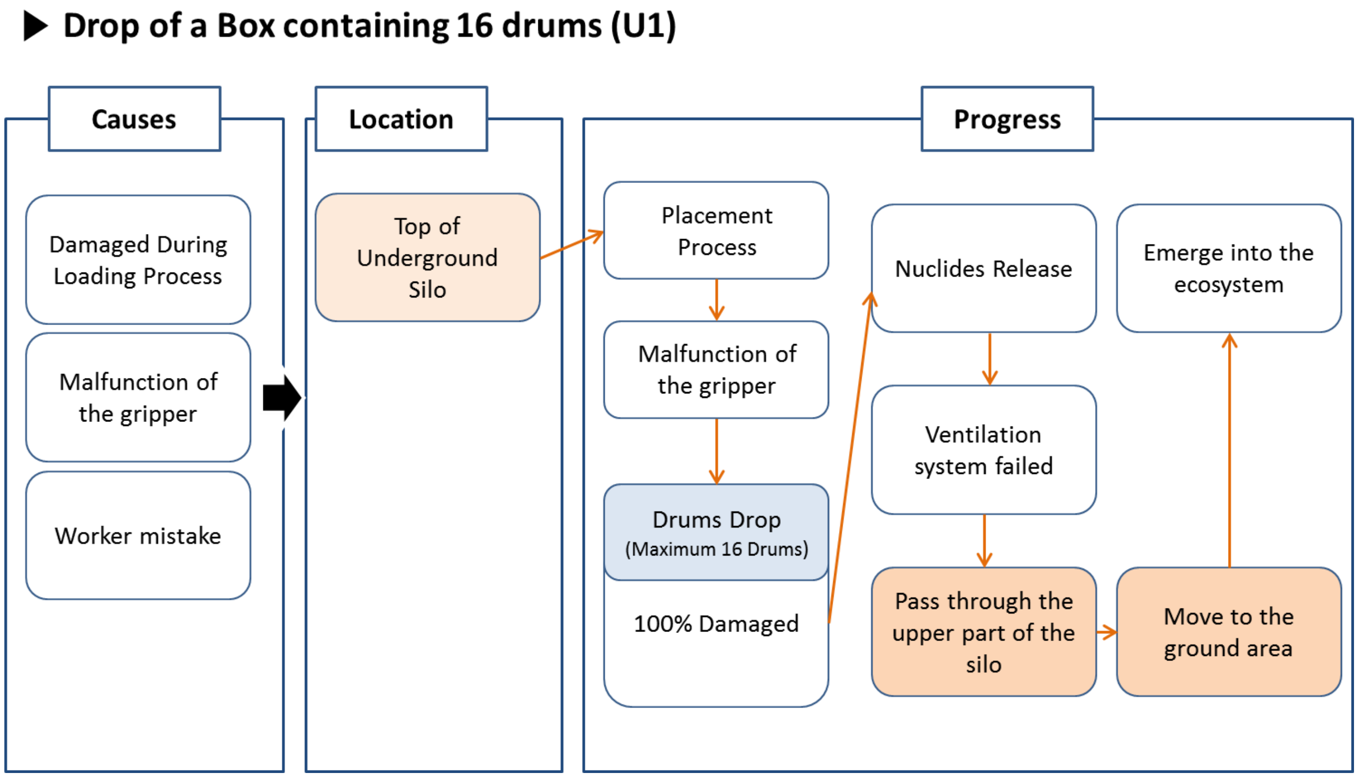

Figure 6.2 Causes and progress of drop of a box scenario

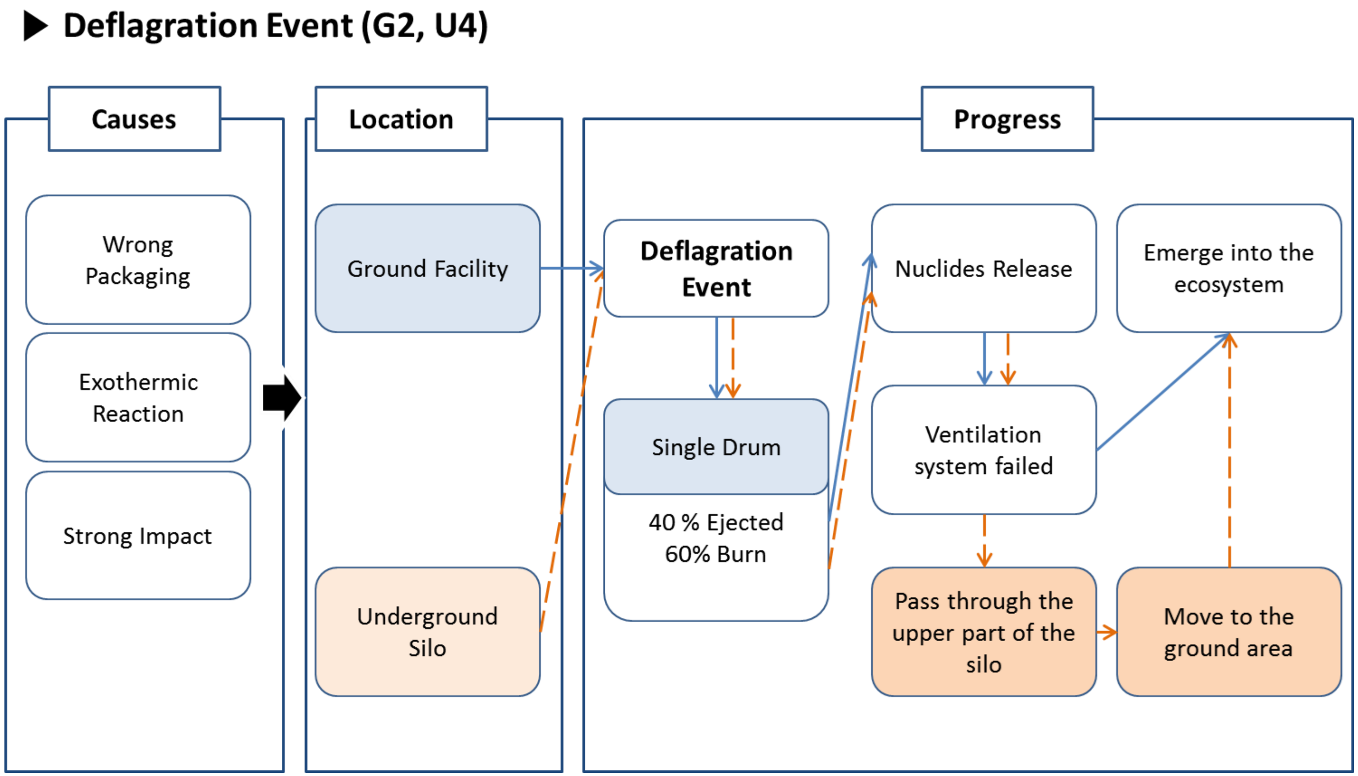

Figure 6.3 Causes and progress of deflagration scenario

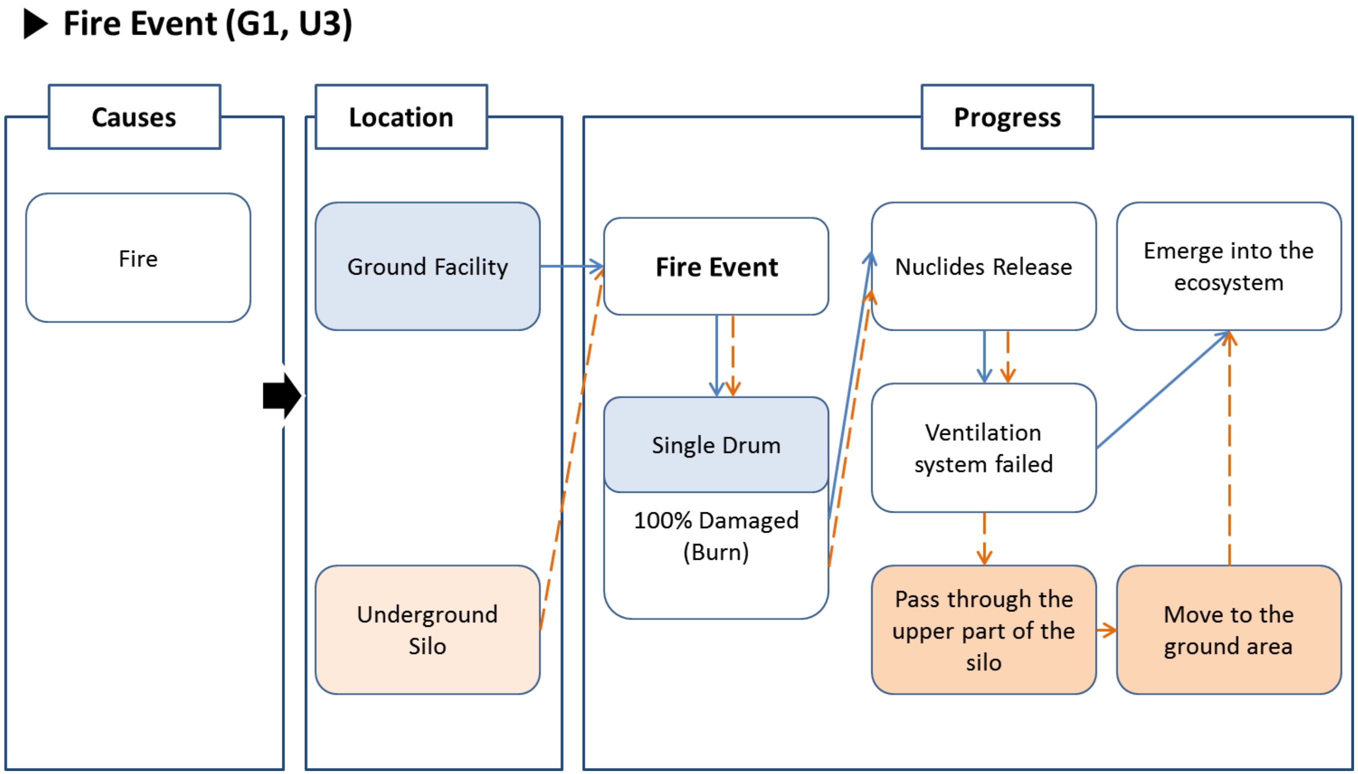

Figure 6.4 Causes and progress of fire scenario

▶ **Seismic Event (U5)**

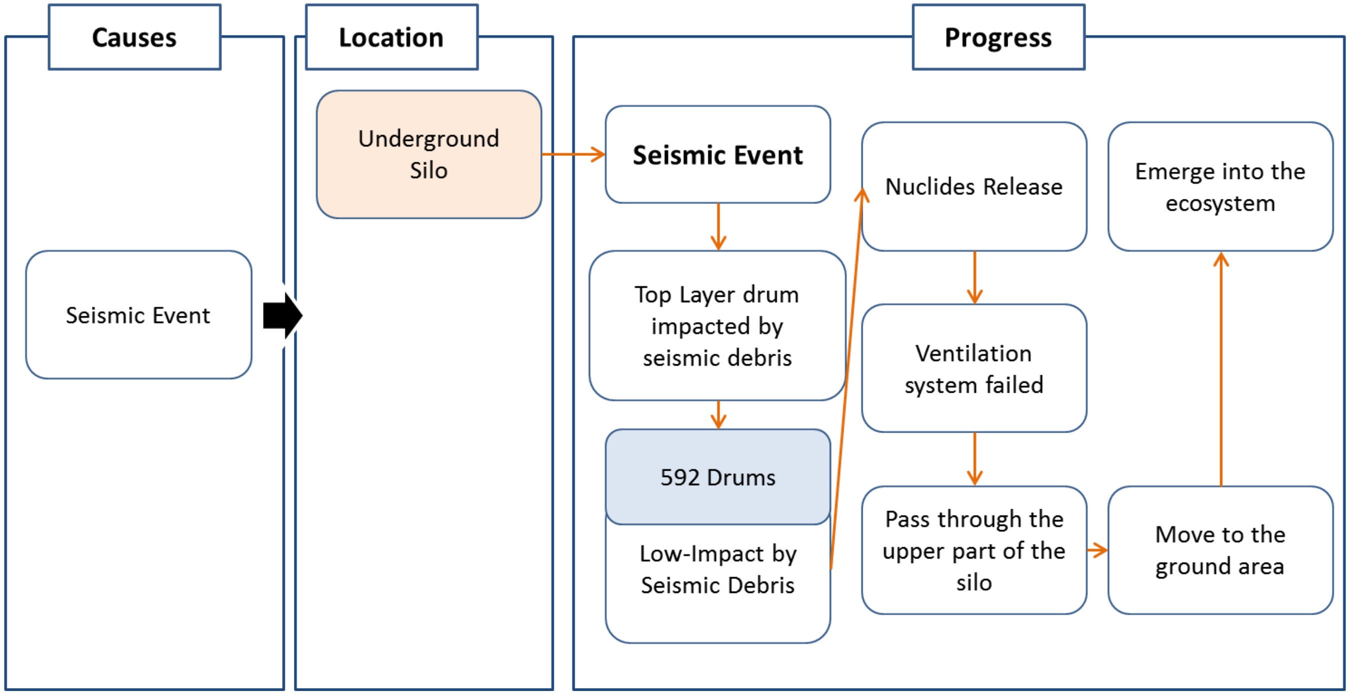

Figure 6.5 Causes and progress of seismic event scenario

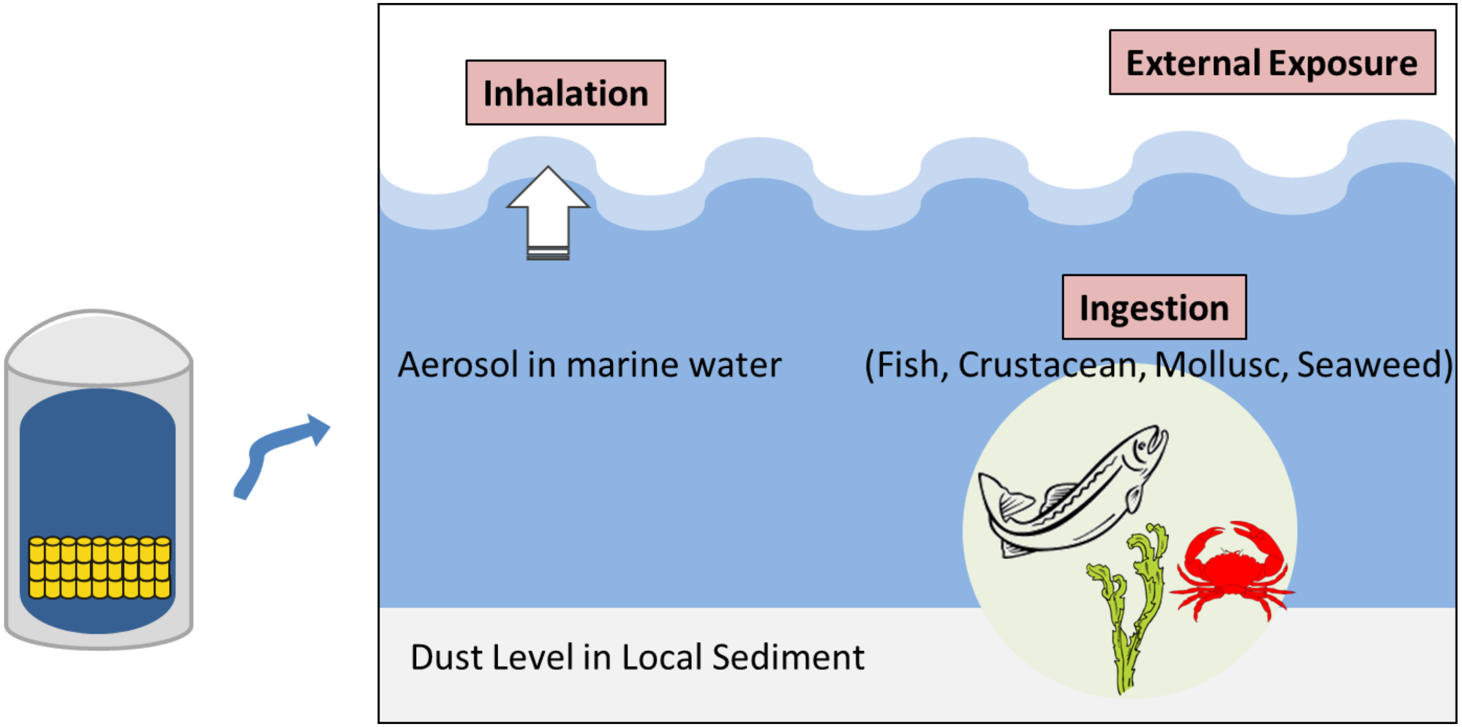

Figure 6.6 Nuclide exposure pathway for flooding scenario

Table 6.1 Summarized input data

<table>
<tr><th></th><th>Number of Drum</th><th>DR</th><th>ARF*RF</th><th>Reference</th></tr>
<tr><td>A Box Containing 16 Drums Drop</td><td>16</td><td>1.0</td><td>7E-4</td><td rowspan="6">DR: DOE-STD-5506-1007, Preparation of safety basis documents for transuranic waste facilities
Table 4.4.4-1 Container drop and impact damage ratios
Table 4.4.5-1 Damage ratios for containers impacted by seismic debris
Appendix B. Idaho deflagration experiment
ARF*RF: DOE Handbook 3010-94, Airborne release fractions/rates and respirable fractions for nonreactor nuclear facilities
ARF*RF value applicable to waste accidents</td></tr>
<tr><td>Damage to Loaded Drum</td><td>10</td><td>1E-3</td><td>7E-5</td></tr>
<tr><td rowspan="2">Deflagration</td><td rowspan="2">1</td><td>0.4(Ejected)</td><td>1E-2</td></tr>
<tr><td>0.6(Burn)</td><td>1E-6</td></tr>
<tr><td>Fire</td><td>100</td><td>1.0</td><td>1E-6</td></tr>
<tr><td>Seismic Event</td><td>16700
(592)</td><td>1E-3</td><td>7E-5</td></tr>
</table>

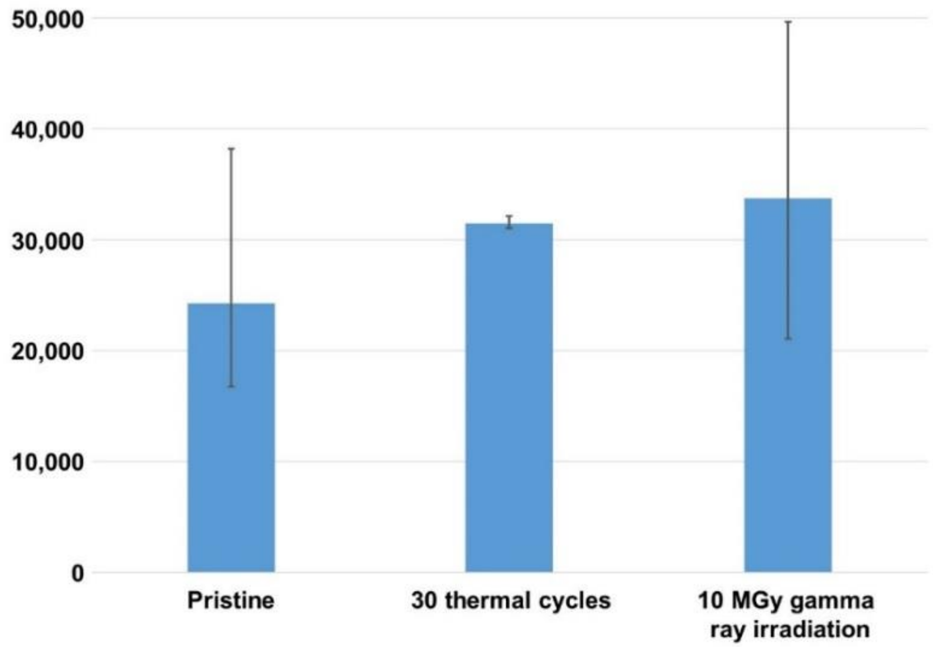

Figure 6.7 Compressive strength [psi] of the monolithic cylindrical glasses: pristine, 30 thermal cycles, and 10 MGy gamma ray irradiation [5]

6.3 Result and Discussions

Figure 6.7 and Figure 6.8 shows the result of GoldSim® modeling for eight accident scenarios during the disposal operation of PyroGreen vitrified waste from near surface facility to underground silo. In the case of Flooding the effects of the radionuclide migration into the far ocean were calculated, only the impact on the public was derived.

Because the all scenarios were evaluated in the same weather conditions, the results were influenced by the calculated source term. The main factor affecting the results is the damage ratio which determines the total amount of nuclides to release. There was little difference in multiplication of airborne release rate and respirable rate except drop scenario and deflagration scenario. Because they assume a situation that the drum is completely broken. Particularly in explosion scenarios, the effects of ejected radionuclides are significant.

Figure 6.9 shows a comparison of these two results. The dose standard for the general public and the worker is 5mSv and 50mSv respectively. It can confirm that all the results satisfy these criteria.

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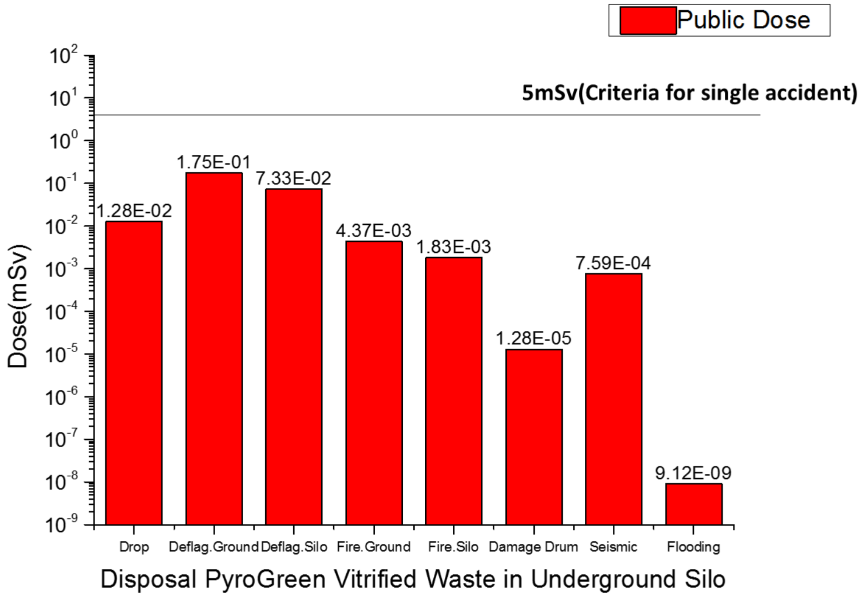

Figure 6.8 Public dose for disposal PyroGreen vitrified waste

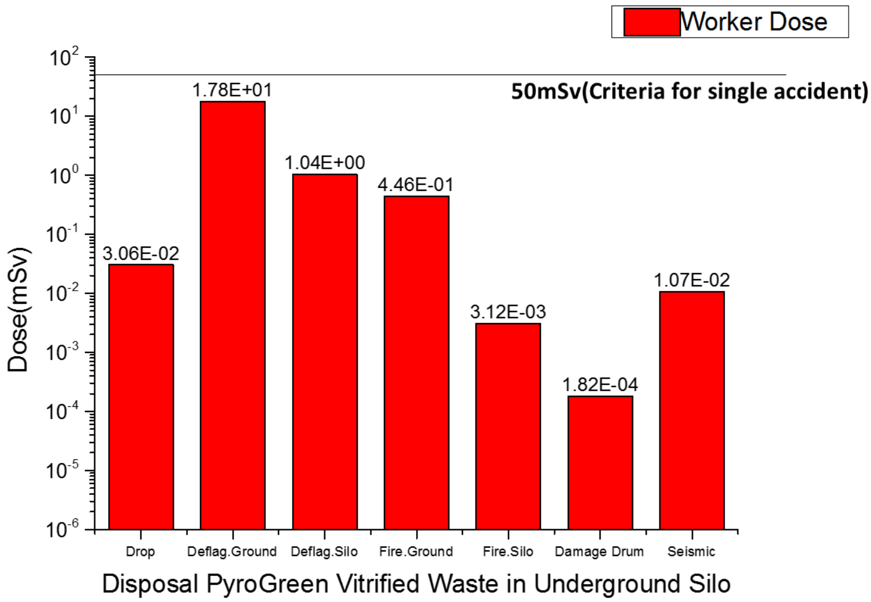

Figure 6.9 Worker dose for disposal PyroGreen vitrified waste

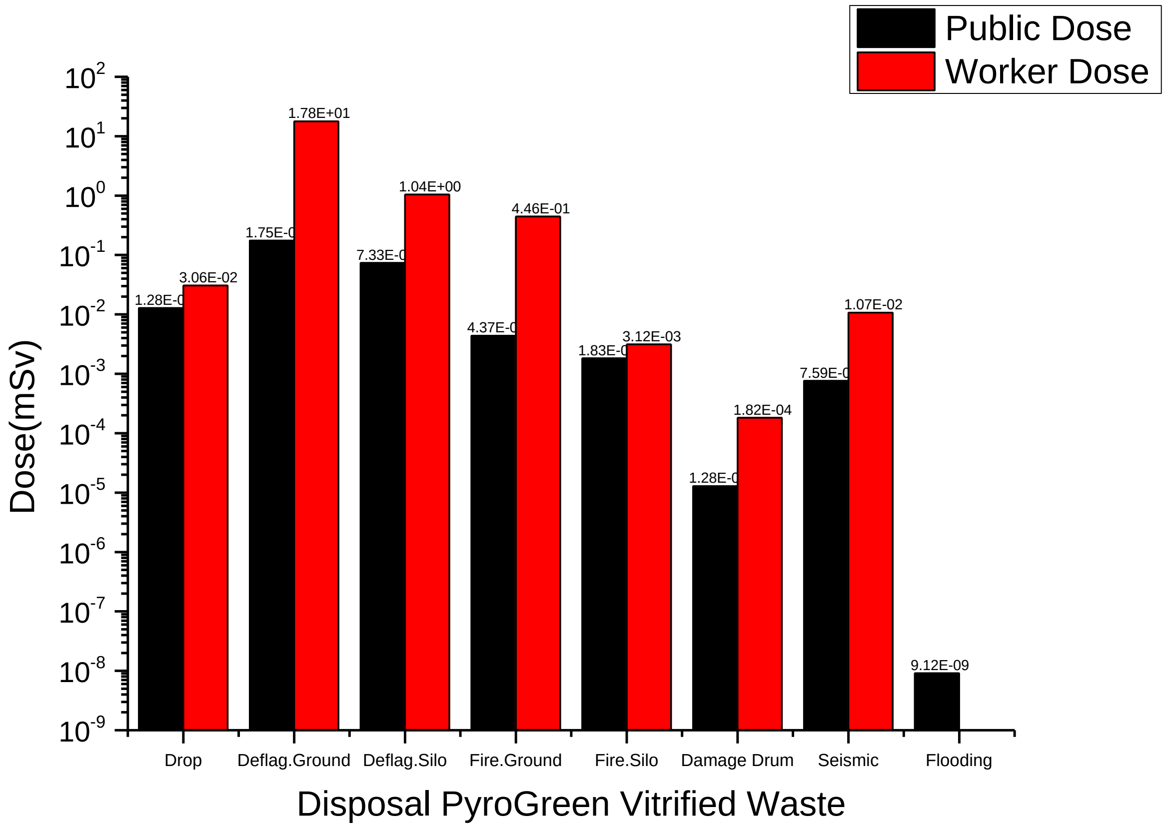

Figure 6.10 Comparison of public dose and worker dose

7. Conclusion and Future work

7.1 Conclusion

This thesis has been focused on the safety assessment of disposal operation of PyroGreen waste at a hypothetical intermediate level waste repository. The assessment has been made by the following steps; model development, model benchmark and data scenario construction, scenario model data base, model application. The geometry and disposal environment for the hypothetical underground ILW repository are patterned after data from the Gyeongju underground repository, which is the first radioactive waste repository in Korea.

Both mitigative and preventive measures have been considered in the scenario development and evaluation. However, this thesis study has focused on the scenario development by accepting available features. Finally selected scenarios for this study include as follows; fire, deflagration, drop of a box containing drums, seismic event, flooding, rock drop. Six accident scenarios were evaluated during the disposal operation of PyroGreen vitrified waste from near surface facility to underground silo.

The radiation release source term has been calculated by the five multiplication parameters including materials at risk, damage ratio, airborne release fraction, respirable fraction and leak path factor. To simulate the release of radionuclides based on the Gaussian plume model the thesis study employed the atmospheric dispersion factor for quantifying airborne concentration [Bq/m3] to unit release rate [Bq/s].

Nuclear Safety and Security Commission Notice No. 2012-19, “Survey on Evaluation Criteria of Meteorological Conditions of Reactor Site” has been taken as a method for evaluating nuclides transport using atmospheric dispersion factor during hypothetical accident based on U.S. NRC Regulatory Guideline 1.145. Atmospheric dispersion factor is affected by wind speed, atmospheric stability, and distance from accident point. These data are simulated by GoldSim® Radionuclide Transport module which provides solution for contaminant transport equation.

To validate the performance of GoldSim® model, a benchmarking has been performed on seismic event and fire scenarios through application to Gyeongju near surface disposal facility. The public dose results were compared with the available results of the radiation environmental impact assessment. The reference used for benchmarking is the second stage disposal facility environmental impact assessment conducted by the Korea Radioactive Waste Agency (KORAD) [2]. Predicted public dose results by GoldSim® model were compared with the results of the radiation environmental impact assessment and it was confirmed that they agreed with each other well within 2.5%.

Using GoldSim® model, fire and explosion scenarios, which are single drum damage scenarios, are assessed for both underground and surface facilities, as the impact is greater if it occurs at a surface facility closer to workers and public. For all scenarios, it is assumed that the ventilation system fails for pessimistic evaluation. In the case of accidents occurring in the underground silo, the all radionuclides pass through upper part of the silo and move to the ground area.

As shown in Table 7.1, all results confirm that they meet the respective regulatory standards with high safety margin. As a result, the safety of PyroGreen waste disposal in an intermediate level waste repository has been demonstrated for six plausible scenarios.

Through the results, it can be confirmed that PyroGreen wastes possess advantage in safety assurance during the repository operation phase disposing it in the ILW repository.

7.2 Future Work

The developed model, in this thesis, needs to be improved with more detailed information that can be acquired by detailed design studies for the repository. Because of the lack of data on the repository operation, the current accident scenarios are based on empirical estimates. But if FEPs (Features, Events and Processes) can be fully developed including human behaviors for the operation phase, an integrated evaluation system for total scenarios can be established based on the FEP.

Also, it can be extended to probabilistic approaches using extensive data, if available. Furthermore, model can be applied to high level waste disposal facilities by acquiring experimental data on disposal container.

Table 7.1 Demonstrated safety assessment result of PyroGreen waste disposal operation for accident scenarios by using GoldSim® model

		Operation Period(~100year)		Institutional Control Period (~300 year)	Uncontrolled Period
		Above Ground Station	Underground Silo		
Natural Accident	Leaching & Migration		O	O	O
	Seismic Event		O	O	O
	Flood		O		
Manmade Accident	Fire	O	O		
	Deflagration	O	O		
	Drop		O		

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Appendixes. GoldSim® Input Data

1. Derived Atmospheric Dispersion Factor

1000m						
wind speed	A	B	C	D	E	F
0.5	6.630E-06	3.679E-05	9.789E-05	1.486E-04	1.954E-04	3.344E-04
1.0	3.315E-06	1.840E-05	4.895E-05	7.430E-05	9.772E-05	1.672E-04
1.5	2.210E-06	1.226E-05	3.263E-05	4.953E-05	6.515E-05	1.115E-04
2.0	1.657E-06	9.198E-06	2.447E-05	3.715E-05	4.886E-05	8.359E-05
2.5	1.326E-06	7.358E-06	1.958E-05	3.397E-05	4.467E-05	7.642E-05
3.0	1.105E-06	6.132E-06	1.632E-05	3.302E-05	4.343E-05	7.430E-05
3.5	9.471E-07	5.256E-06	1.398E-05	3.397E-05	4.467E-05	7.642E-05
4.0	8.287E-07	4.599E-06	1.224E-05	3.715E-05	4.886E-05	8.359E-05
4.5	7.366E-07	4.088E-06	1.088E-05	4.403E-05	5.791E-05	9.907E-05
5.0	6.630E-07	3.679E-06	9.789E-06	5.944E-05	7.818E-05	1.337E-04
800m						
wind speed	A	B	C	D	E	F
0.5	1.233E-05	5.724E-05	1.447E-04	2.153E-04	2.803E-04	4.836E-04
1.0	6.164E-06	2.862E-05	7.235E-05	1.077E-04	1.402E-04	2.418E-04
1.5	4.109E-06	1.908E-05	4.823E-05	7.177E-05	9.345E-05	1.612E-04
2.0	3.082E-06	1.431E-05	3.617E-05	5.383E-05	7.008E-05	1.209E-04
2.5	2.466E-06	1.145E-05	2.894E-05	4.921E-05	6.408E-05	1.105E-04
3.0	2.055E-06	9.540E-06	2.412E-05	4.785E-05	6.230E-05	1.075E-04
3.5	1.761E-06	8.177E-06	2.067E-05	4.921E-05	6.408E-05	1.105E-04
4.0	1.541E-06	7.155E-06	1.809E-05	5.383E-05	7.008E-05	1.209E-04
4.5	1.370E-06	6.360E-06	1.608E-05	6.380E-05	8.306E-05	1.433E-04
5.0	1.233E-06	5.724E-06	1.447E-05	8.612E-05	1.121E-04	1.935E-04
500m						
wind	A	B	C	D	E	F

speed						
0.5	4.430E-05	1.424E-04	3.224E-04	4.731E-04	6.030E-04	1.055E-03
1.0	2.215E-05	7.119E-05	1.612E-04	2.366E-04	3.015E-04	5.277E-04
1.5	1.477E-05	4.746E-05	1.075E-04	1.577E-04	2.010E-04	3.518E-04
2.0	1.107E-05	3.559E-05	8.060E-05	1.183E-04	1.507E-04	2.639E-04
2.5	8.860E-06	2.847E-05	6.448E-05	1.081E-04	1.378E-04	2.412E-04
3.0	7.383E-06	2.373E-05	5.373E-05	1.051E-04	1.340E-04	2.345E-04
3.5	6.328E-06	2.034E-05	4.606E-05	1.081E-04	1.378E-04	2.412E-04
4.0	5.537E-06	1.780E-05	4.030E-05	1.183E-04	1.507E-04	2.639E-04
4.5	4.922E-06	1.582E-05	3.582E-05	1.402E-04	1.787E-04	3.127E-04
5.0	4.430E-06	1.424E-05	3.224E-05	1.893E-04	2.412E-04	4.222E-04
300m						
wind speed	A	B	C	D	E	F
0.5	1.624E-04	3.626E-04	7.224E-04	1.129E-03	1.404E-03	2.480E-03
1.0	8.119E-05	1.813E-04	3.612E-04	5.643E-04	7.022E-04	1.240E-03
1.5	5.413E-05	1.209E-04	2.408E-04	3.762E-04	4.681E-04	8.267E-04
2.0	4.059E-05	9.065E-05	1.806E-04	2.821E-04	3.511E-04	6.201E-04
2.5	3.248E-05	7.252E-05	1.445E-04	2.580E-04	3.210E-04	5.669E-04
3.0	2.706E-05	6.043E-05	1.204E-04	2.508E-04	3.121E-04	5.512E-04
3.5	2.320E-05	5.180E-05	1.032E-04	2.580E-04	3.210E-04	5.669E-04
4.0	2.030E-05	4.532E-05	9.031E-05	2.821E-04	3.511E-04	6.201E-04
4.5	1.804E-05	4.029E-05	8.027E-05	3.344E-04	4.161E-04	7.349E-04
5.0	1.624E-05	3.626E-05	7.224E-05	4.514E-04	5.617E-04	9.921E-04
100m						
wind speed	A	B	C	D	E	F
0.5	1.161E-03	1.695E-03	2.462E-03	8.053E-03	9.445E-03	1.622E-02
1.0	5.807E-04	8.477E-04	1.231E-03	4.027E-03	4.722E-03	8.109E-03
1.5	3.871E-04	5.652E-04	8.208E-04	2.684E-03	3.148E-03	5.406E-03
2.0	2.903E-04	4.239E-04	6.156E-04	2.013E-03	2.361E-03	4.054E-03
2.5	2.323E-04	3.391E-04	4.925E-04	1.841E-03	2.159E-03	3.707E-03
3.0	1.936E-04	2.826E-04	4.104E-04	1.790E-03	2.099E-03	3.604E-03

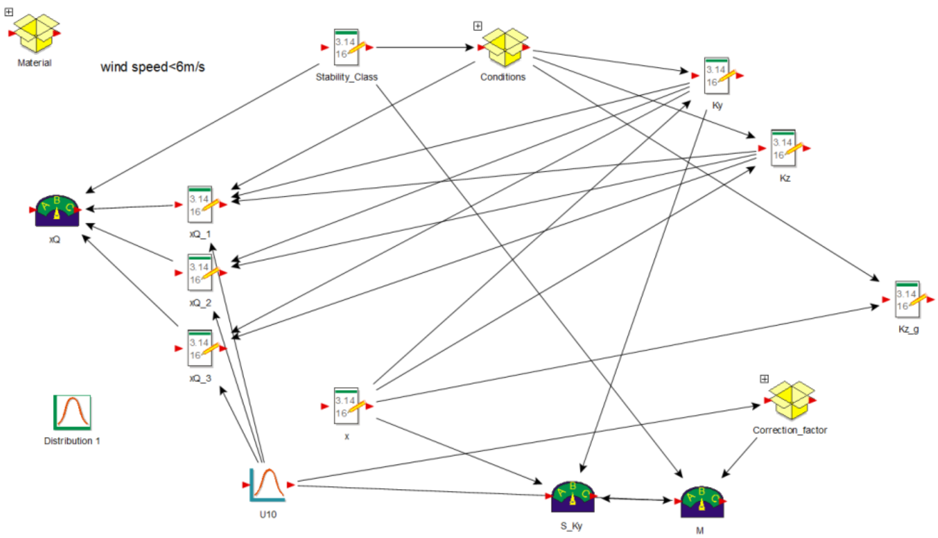
3.5	1.659E-04	2.422E-04	3.518E-04	1.841E-03	2.159E-03	3.707E-03
4.0	1.452E-04	2.119E-04	3.078E-04	2.013E-03	2.361E-03	4.054E-03
4.5	1.290E-04	1.884E-04	2.736E-04	2.386E-03	2.798E-03	4.805E-03
5.0	1.161E-04	1.695E-04	2.462E-04	3.221E-03	3.778E-03	6.487E-03

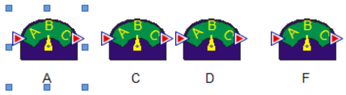
2. Input Data for Scenarios

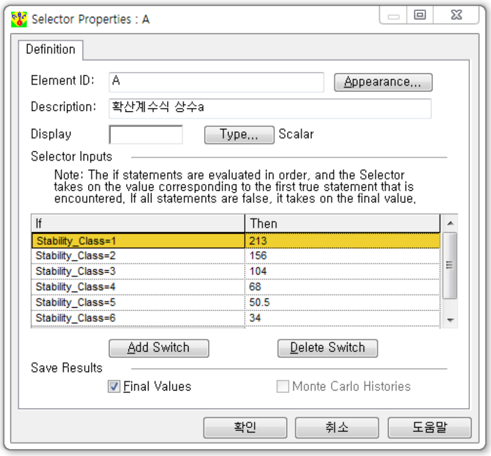
1) Input Data Table

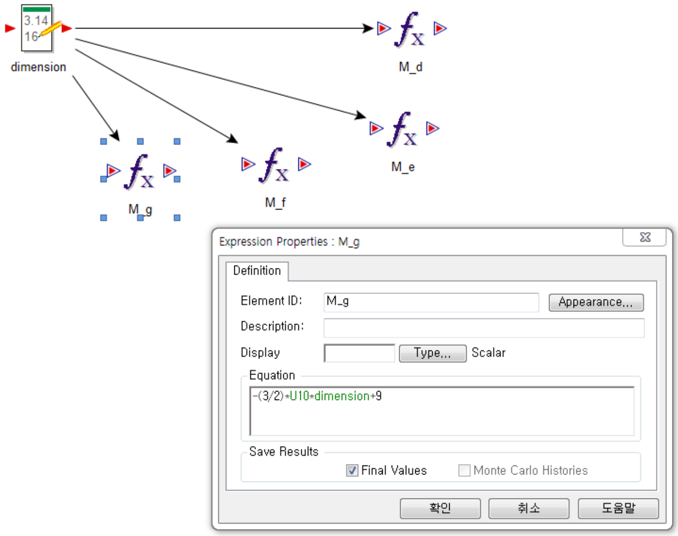
<table>
<tr><th rowspan="2">Location</th><th rowspan="2">Scenario</th><th rowspan="2">Number of Drum</th><th rowspan="2">DR</th><th rowspan="2">ARF *RF</th><th rowspan="2">Multiplication</th><th colspan="2">Atmospheric Dispersion Factor</th></tr>
<tr><th>Worker</th><th>Public</th></tr>
<tr><td rowspan="6">Underground</td><td>Drum Drop</td><td>16</td><td>1.0</td><td>7E-4</td><td>1.12E-2</td><td rowspan="6">1.53E-3</td><td rowspan="6">1.08E-4</td></tr>
<tr><td>Damage to Drum</td><td>10</td><td>1E-3</td><td>7E-5</td><td>7.00E-7</td></tr>
<tr><td rowspan="2">Deflagration</td><td rowspan="2">1</td><td>0.4 (Ejected)</td><td>1E-2</td><td>4.00E-3</td></tr>
<tr><td>0.6 (Burn)</td><td>1E-6</td><td>6.00E-7</td></tr>
<tr><td>Fire</td><td>1</td><td>1.0</td><td>1E-6</td><td>1.00E-4</td></tr>
<tr><td>Seismic Event</td><td>592</td><td>1E-3</td><td>7E-5</td><td>4.14E-5</td></tr>
<tr><td>Near Surface</td><td>Deflagration</td><td>1</td><td>0.4</td><td>1E-2</td><td>4.00E-3</td><td>2.63E-2</td><td>1.88E-3</td></tr>
</table>

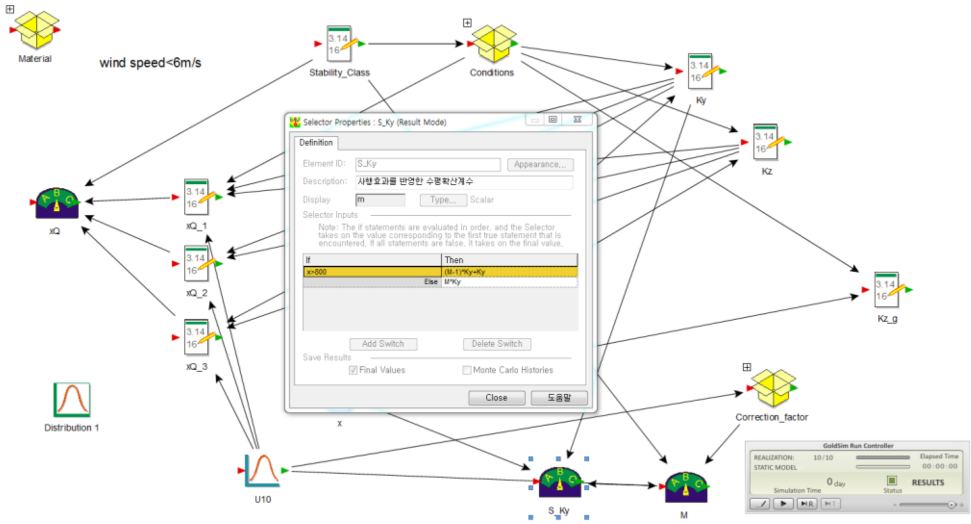
2) GoldSim Model

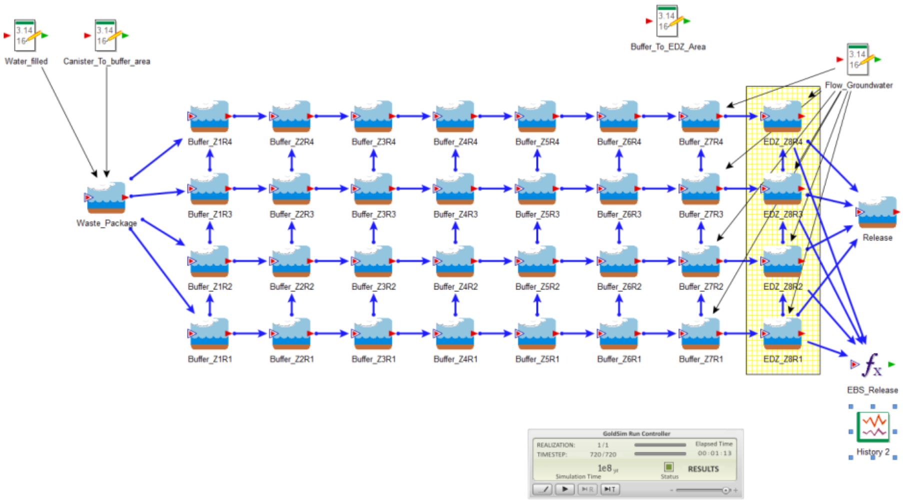


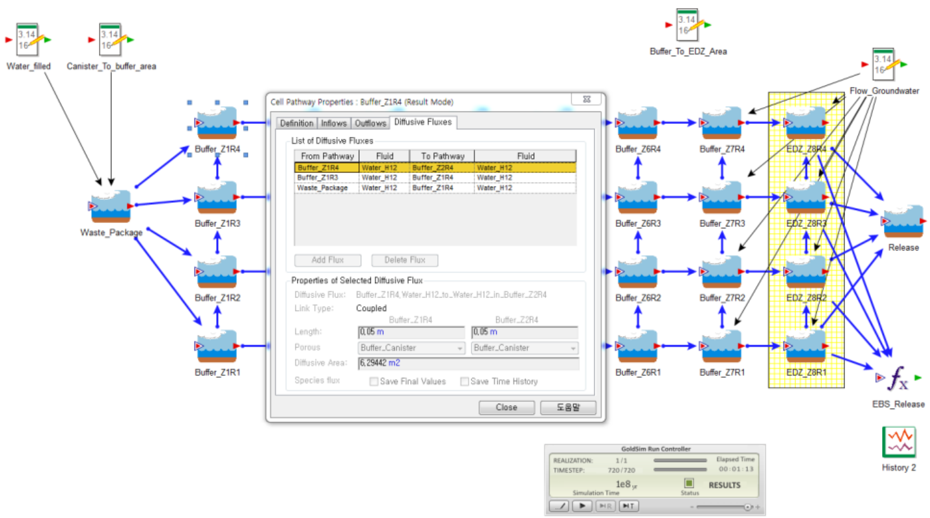


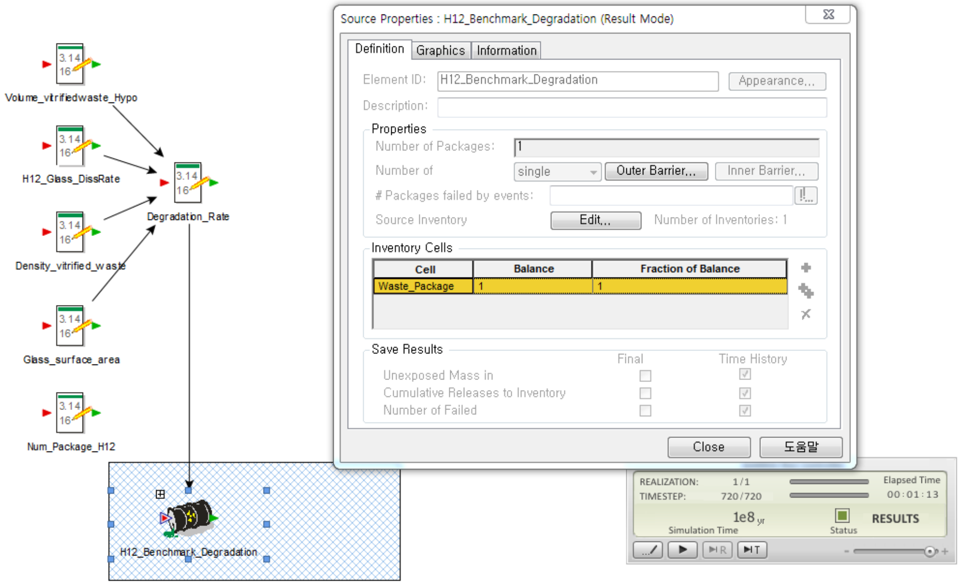


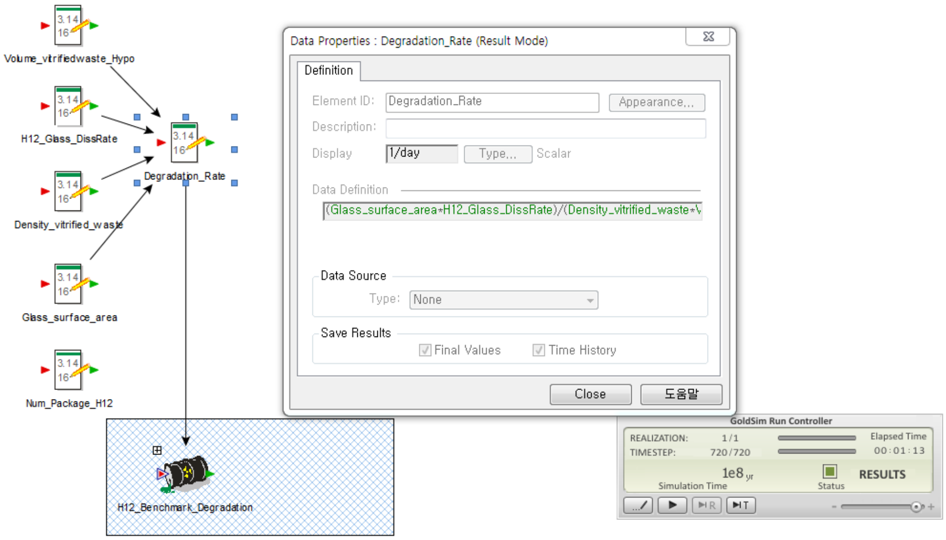

dimension
M_d
M_e
M_f
M_g
Expression Properties : M_g
Definition
Element ID: M_g
Appearance...
Description:
Display
Type...
Scalar
Equation
-(3/2)+U10+dimension+9
Save Results
Final Values
Monte Carlo Histories
확인
취소
도움말


Material
wind speed<6m/s
Stability_Class
Conditions
Ky
Kz
Kz_g
xQ
xQ_1
xQ_2
xQ_3
Distribution 1
U10
S_Ky
M
Correction_factor
x
Selector Properties : S_Ky (Result Mode)
Definition
Element ID: S_Ky
Appearance...
Display
m
Type...
Scalar
Selector Inputs
If
Then
x>800
(M-1)*Ky+Ky
Else
M*Ky
Add Switch
Delete Switch
Save Results
Final Values
Monte Carlo Histories
Close
도움말


Water_filled
Canister_To_buffer_area
Buffer_To_EDZ_Area
Flow_Groundwater
Waste_Package
Buffer_Z1R4
Buffer_Z2R4
Buffer_Z3R4
Buffer_Z4R4
Buffer_Z5R4
Buffer_Z6R4
Buffer_Z7R4
EDZ_Z8R4
Buffer_Z1R3
Buffer_Z2R3
Buffer_Z3R3
Buffer_Z4R3
Buffer_Z5R3
Buffer_Z6R3
Buffer_Z7R3
EDZ_Z8R3
Buffer_Z1R2
Buffer_Z2R2
Buffer_Z3R2
Buffer_Z4R2
Buffer_Z5R2
Buffer_Z6R2
Buffer_Z7R2
EDZ_Z8R2
Buffer_Z1R1
Buffer_Z2R1
Buffer_Z3R1
Buffer_Z4R1
Buffer_Z5R1
Buffer_Z6R1
Buffer_Z7R1
EDZ_Z8R1
Release
EBS_Release
History 2
GoldSim Run Controller
RESULTS


Water_filled
Canister_To_buffer_area
Buffer_To_EDZ_Area
Flow_Groundwater
Waste_Package
Buffer_Z1R4
Buffer_Z1R3
Buffer_Z1R2
Buffer_Z1R1
Cell Pathway Properties : Buffer_Z1R4 (Result Mode)
Definition
Inflows
Outflows
Diffusive Fluxes
List of Diffusive Fluxes
From Pathway
Fluid
To Pathway
Fluid
Buffer_Z1R4
Water_H12
Buffer_Z2R4
Water_H12
Buffer_Z1R3
Water_H12
Buffer_Z1R4
Water_H12
Waste_Package
Water_H12
Buffer_Z1R4
Water_H12
Add Flux
Delete Flux
Properties of Selected Diffusive Flux
Diffusive Flux:
Link Type:
Coupled
Length:
Porous
Diffusive Area:
Species flux
Save Final Values
Save Time History
Close
Buffer_Z6R4
Buffer_Z7R4
EDZ_Z8R4
Buffer_Z6R3
Buffer_Z7R3
EDZ_Z8R3
Buffer_Z6R2
Buffer_Z7R2
EDZ_Z8R2
Buffer_Z6R1
Buffer_Z7R1
EDZ_Z8R1
Release
EBS_Release
History 2
GoldSim Run Controller
RESULTS


Volume_vitrifiedwaste_Hypo
H12_Glass_DissRate
Degradation_Rate
Density_vitrified_waste
Glass_surface_area
Num_Package_H12
H12_Benchmark_Degradation
Source Properties : H12_Benchmark_Degradation (Result Mode)
Definition
Graphics
Information
Element ID:
H12_Benchmark_Degradation
Appearance...
Description:
Properties
Number of Packages:
Number of
single
Outer Barrier...
Inner Barrier...
Packages failed by events:
Source Inventory
Edit...
Number of Inventories: 1
Inventory Cells
Cell
Balance
Fraction of Balance
Waste_Package
Save Results
Final
Time History
Unexposed Mass in
Cumulative Releases to Inventory
Number of Failed
Close
도움말
REALIZATION: 1/1
TIMESTEP: 720/720
Elapsed Time 00:01:13
1e8 yr
Simulation Time
Status
RESULTS


Volume_vitrifiedwaste_Hypo
H12_Glass_DissRate
Degradation_Rate
Density_vitrified_waste
Glass_surface_area
Num_Package_H12
H12_Benchmark_Degradation
Data Properties : Degradation_Rate (Result Mode)
Definition
Element ID:
Degradation_Rate
Appearance...
Description:
Display
1/day
Type...
Scalar
Data Definition
(Glass_surface_area*H12_Glass_DissRate)/(Density_vitrified_waste*V
Data Source
Type:
None
Save Results
Final Values
Time History
Close
도움말
GoldSim Run Controller
REALIZATION: 1/1
TIMESTEP: 720/720
Elapsed Time 00:01:13
1e8 yr
Simulation Time
Status
RESULTS

국문 요약서

본 논문에서 지하 중준위폐기물 동굴처분장에 PyroGreen 폐기물을 처분 하였을 때, 발생할 수 있는 운영 중 사고에 대한 안전성 평가를 수행하였다. PyroGreen은 기검증된 한국원자력연구원의 KIEP-21 파이로공정을 바탕으로, 서울대학교 핵변환에너지연구센터에서 개발한 공정이다. PyroGreen은 제염계수의 추가적인 확보를 통하여 최종폐기물이 WIPP의 처분 승인 기준을 충족한다. 평가의 대상이 되는 가상의 PyroGreen 폐기물 처분장은 국내 유일한 방사성 폐기물 처분장인 경주 처분장의 데이터를 기반으로 설정되었다.

방사성 폐기물 처분장의 안전성 평가는 평가 대상 시기에 따라 폐쇄 후 저장 기간에 대한 안전성 평가와 운영기간에 대한 안전성 평가로 구분할 수 있다. 지금까지 방사성 폐기물 처분과 관련한 주된 연구는 전자에 대한 장기간 안전성 평가의 불확실성을 줄이기 위한 노력에 초점을 맞추어 이루어졌다. 운영 중 상태의 경우 높은 감시 및 관리 하에 있기 때문에 후자에 대해서는 비교적 많은 연구가 진행되지 않았다.

그러나 2014년 2월 미국의 TRU 폐기물 처분 시설 WIPP(Waste Isolation Pilot Plant)에서 발생한 트럭 화재 사고와 폐기물드럼 폭발 사고 이후 처분장 운영 기간의 안전성 평가에 대한 관심이 높아지고 있다. 특히 폭발 사건의 경우 폐기물 포장, 검수, 필터시스템의 연속적인 실패기 방사성 물질의 누출까지 이어졌다는 점이 중요하게 지적되었다. 미국 에너지부(DOE)는 사고 이후 조사 보고서를 통해 사고의 원인이 된 12가지의 위험 영역을 언급하며 다중의 관리/감독 시스템의 실패와 사전 위험 분석이 부족했음을 지적하였다. 이러한 사례를 보았을 때, 처분장

운영 중 사고 발생 시 충분한 안전을 확보 할 수 있는지, 또한 기존 연구에서 논의된 사고 시나리오가 충분한지 여부를 논의할 필요가 있음을 알 수 있다.

본 논문에서 분석한 사고 시나리오는 기존의 운영 중 사고 안전성 평가 시나리오 및, 기존시나리오 개발 과정에서 제외된 시나리오와 실제로 발생한 사고를 기반으로 설정되었다. 또한 가상의 처분장의 경우, 처분시설이 해수면 아래에 위치하기 때문에 홍수 시나리오도 추가되어 평가되었다. 따라서 본 연구에서 고려한 최종 시나리오는 화재(지상/지하), 폭발(지상/지하), 드럼 적치 중 낙하, 적치된 드럼의 손상, 지진, 홍수의 총 8가지이다.

각 사고 시나리오 별 누출되는 핵종의 양은, 5인자 공식에 의하여 도출되었으며, 가우시안 플룸 모델을 바탕으로 대기확산인자를 계산하였다. 이는 미국 NRC의 규제 가이드라인 1.145를 바탕으로 한 원자력안전위원회 고시 제 2014-25호 ‘원자로시설 부지의 기상조건에 대한 조사/평가 기준’에 따른 것이다. 대기확산인자는 풍속, 기온감율, 대기안정등급, 사고 지점까지의 거리 등에 영향을 받는다. 위의 선원항과 대기확산인자를 바탕으로 하여, 핵종의 누출로 인해 작업자와 일반인에게 미치는 영향이 GoldSim® 코드를 이용하여 계산되었다.

GoldSim® 코드의 적용성 검증을 위해 경주 표층처분시설에 적용하여 해당 처분장 안전성 평가 결과와 비교하였으며 오차범위 2.5% 이내로 양 결과가 서로 잘 일치함을 확인하였다. 단일용기 손상 시나리오인 화재 및 폭발 시나리오는 지하 및 지상 시설 모두에 대해 평가되었으며, 이는 가까운 지상 시설에서 발생할 경우 영향이 더 클 것으로 예측되기 때문이다. 대기확산의 영향을 보는 모든 시나리오에서, 보수적인 평가를

위하여 환기 시스템은 실패되었다고 가정되었으며, 지하 동굴에서 일어나는 사고의 경우 모든 방사성 핵종은 동굴의 상부를 통과하여 지표로 이동하는 것을 가정하였다.

일반인과 작업자에 대한 모든 결과는 높은 여유도를 가지고 단일사고 발생시의 규제기준인 5mSv와 50mSv를 각각 만족함이 확인되었으며, 지하 중준위 처분장 파이로 그린 폐기물 처분에 대한 운영 안전성을 입증하였다.

주요어: 운영 중 안전성 평가, PyroGreen, 중준위 방사성폐기물 처분, 대기확산모델

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